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# Single-Pilot Workload Management in Entry-Level Jets

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16. Abstract


Researchers from the NASA Ames Flight Cognition Lab and the FAA's Flight Deck Human Factors Research Laboratory at the Civil Aerospace Medical Institute (CAMI) examined task and workload management by single pilots in Very Light Jets (VLJs), also called Entry-Level Jets (ELJs). Fourteen certificated Cessna Citation Mustang (C510-S) pilots flew an experimental flight with two legs involving high workload management under Instrument Flight Rules (IFR) in a Cessna Citation Mustang ELJ level 5 flight training device at CAMI. Eight of the pilots were Mustang owner-operators, and the other six flew the Citation Mustang as part of their jobs as professional pilots. In addition to the Cessna Citation Mustang simulator, data collection included instantaneous self-assessment of perceived workload, NASA Task Load Index (TLX) workload measures, researcher observations, final debriefing interviews, and three questionnaires: Cockpit Set-up Preferences, Demographics, and Automation Experiences and Perceptions.

To facilitate analysis, the major high workload tasks during the cruise portion of flight were grouped into four events. Approximately two-thirds of the tasks within the four events were accomplished by the participants with no difficulties. Though all participants committed a variety of errors during all four high workload events (e.g., readback error, airspeed violation), most errors were not directly related to overall task success. We did find a significant effect on task performance success related to hours of experience only for the first event. We also found that some type of error using the G1000 avionics was at the root of the problem for most participants who had difficulty accomplishing one or more of the tasks. All participants committed a variety of errors during all four high workload events (e.g., readback error, airspeed violation), but most were not directly related to overall task success. Implications of the findings are discussed, and techniques demonstrated by our participants that we have characterized as "best practices" have been identified. Recommended strategies for automation use and countermeasures to task overload and workload breakdowns have also been provided.


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As part of this study, we relied on the experience of two air traffic control subject matter experts (SMEs), Art Gilman and Greg Elwood. In addition, we sought guidance during study design and data analysis from our Garmin G1000/Cessna 510 Citation Mustang aircraft pilot SME, Dave Fry. Their expertise contributed greatly to this project.

We thank Jerry Ball for programming the scenarios developed by NASA into the Cessna 510 Citation Mustang simulator, assisting with data collection, and trouble-shooting during the experiment. Our appreciation also goes to Kali Holcomb for her support with data collection and working behind the scenes during the experiment. Thank you is also due to Captain Randy Phillips (ret.) and Dr. Lynne Martin, who were centrally involved in the development of earlier versions of the experimental flight scenarios and associated task analyses. We are also grateful for the help extended by Dr. Durand Begault in conducting the voice analyses for this study.

Finally, we extend our sincere appreciation to the Cessna Mustang pilots who completed questionnaires and who served as participants in this study. Their desire to further the cause of aviation safety, their willingness to participate, and the insights they so generously shared, were essential to the success of the study. We are very grateful.

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## ACRONYMS AND ABBREVIATIONS

AC ............Advisory Circular
AC_ID.......Aircraft Identifiers
ADDS........Aviation Digital Data Service
AFM ..........Aircraft Flight Manual
AGL...........Above Ground Level
AIM ...........Aeronautical Information Manual
AIRMETS..Airmen's Meteorological Information
ALAR.........Approach and Landing Accident Reduction
AOM .........Aircraft Operating Manual
AOPA ........Aircraft Owners and Pilots Association
ARTCC......Air Route Traffic Control Centers
ASOS.........Automated Surface Observation System
ATC...........Air Traffic Control
ATIS ..........Automated Terminal Information Service
ATP ...........Airline Transport Pilot
AWOS........Automated Weather Observing System
b/t.............Between
CAMI ........Civil Aerospace Medical Institute
CFIT..........Controlled Flight Into Terrain
CFR...........Code of Federal Regulations
CRM..........Crew Resource Management
CSV...........Comma-Separated Value
DH ............Decision Height
DIS ............Distance
DME .........Distance Measuring Equipment
ELJs ...........Entry Level Jets
EMRRS .....Enhanced Mission Record and Review System
ETA ...........Estimated Time of Arrival
FAA...........Federal Aviation Administration
FAF............Final Approach Fix
FARs..........Federal Aviation Regulations
FL ..............Flight Level
FMS...........Flight Management System
FPL............Flight Plan
FPM...........Feet Per Minute
FSF ............Flight Safety Foundation
FSI .............Flight Safety International
GA .............General Aviation
G/A............Go Around
GPS ...........Global Positioning System
IAF.............Initial Approach Fix
ICAO.........International Civil Aviation Organization
IF ...............Intermediate Fix
ILS .............Instrument Landing System
IFR ............Instrument Flight Rules
IMC...........Instrument Meteorological Conditions
ISA.............Instantaneous Self-Assessment
KML..........Keyhole Markup Language
kts ..............Knots
LAN...........Local Area Network
LINE..........Line Number Variable
LOSA.........Line Operations Safety Audit
MDA .........Minimum Descent Altitude
METARs....Meteorological Aerodrome Report
MFD..........Multi-functional Display
MOE .........Margin Of Error
MSL...........Mean Sea-Level
MTS ..........Movable Type Script
NextGen ....Next Generation Air Transportation System
NMT .........Not More Than
NOAA .......National Oceanic and Atmospheric Administration
NOTAMs...Notices to Airmen
PFD ...........Primary Flight Display
PIREPs.......Pilot Reports
POM..........Pilots Operating Manual
PTS............Practical Test Standards
QRH..........Quick Reference Handbook
RNAV........Area Navigation
RTLX.........Raw NASA Task Load Index Scores
SDHC .......Secure Digital High-Capacity
SIGMETS..Significant Meteorological Information
SRM ..........Single Pilot Resource Management
TAFs ..........Terminal Area Forecasts
TAS............True Airspeed
TDZ ..........Touchdown Zone
TDZE........Touchdown Zone Elevation
TERPS.......Terminal Instrument Approach Procedures
TLX ...........Task Load Index
UNK..........Unknown
VBA...........Visual Basic for Applications
VFR ...........Visual Flight Rules
VLJs...........Very Light Jets
VMC .........Visual Meteorological Conditions
VOR ..........Very High Frequency Omni Directional Radio Range
$V_{ref}$ .............Landing Reference Speed
WAV ..........Waveform Audio File Format
WPT..........Waypoint
WQXGA....Wide Quad Extended Graphics Array

# EXECUTIVE SUMMARY

Researchers from the NASA Ames Flight Cognition Lab and the FAA's Flight Deck Human Factors Research Laboratory at the Civil Aerospace Medical Institute (CAMI) examined task and workload management by single pilots in Very Light Jets (VLJs), also called Entry-Level Jets (ELJs). Fourteen certificated Cessna Citation Mustang (C510-S) pilots flew an experimental flight with two legs involving high workload management under Instrument Flight Rules (IFR) in a Cessna Citation Mustang ELJ level 5 flight training device[1] at CAMI. Eight of the pilots were Mustang owner-operators, and the other six flew the Citation Mustang as part of their jobs as professional pilots. In addition to the Cessna Citation Mustang simulator, data collection included the use of a non-invasive eye tracker (mounted to the glare shield), instantaneous self-assessment of perceived workload, NASA Task Load Index (TLX) workload measures, researcher observations, final debriefing interviews, and three questionnaires: Cockpit Set-up Preferences, Demographics, and Automation Experiences and Perceptions.

This exploratory study of VLJ/ELJ single-pilot workload management and automation use was conducted to answer the following questions:

- How do single pilots in small jets manage their workload?
- Where do they have problems managing their workload and what might be some reasons why?
- Are there any workload management approaches that might be characterized as "best practices" and why?
- How do automation and advanced technologies help or hinder single jet pilots in their workload management and what might be some reasons why?

This study was also intended to generate baseline data to be used relative to future NextGen-oriented studies.

Because of the complex nature of the study and the substantial amount of data analysis required, overall analysis of the data was separated into phases. The analyses described in this report pertain to the management of workload, completion of tasks, and automation use by single pilots flying ELJs during four scripted high workload events occurring during climb out and the en route phase of flight.

The four high workload events analyzed were:

1. setting up the automation to intercept the 208° Broadway (BWZ) radial following the completion of the departure procedure out of Teterboro, NJ (KTEB) in leg one,
2. programming a reroute while at cruise and meeting a waypoint crossing restriction on the initial descent from cruise in leg one,
3. the completion of an expedited descent to accommodate another aircraft with an emergency in leg two, and
4. descent to meet a crossing restriction prior to a waypoint and preparation for the approach into Hot Springs, VA (KHSP) while facilitating communication from a lost pilot who was flying too low for air traffic controllers to hear.

Approximately two-thirds of the major tasks in the four events were accomplished by the participants with no difficulties. Participants who were successful or encountered no problems in accomplishing a task tended to rate their performance much higher than those who were unsuccessful or did have problems, often by a substantial margin. We found no differences in performance due to pilot age or pilot type (owner-operator or professional pilot). Furthermore, we found a significant effect on task performance success related to hours of experience only for the first event. Some type of error using the G1000 avionics was at the root of the problem for most participants who had difficulty accomplishing one or more of the tasks. All participants committed a variety of errors during all four high workload events (e.g., readback error, airspeed violation), but most were not directly related to overall task success. Implications of the findings are discussed, and techniques demonstrated by our participants that we have characterized as "best practices" have been identified. Recommended strategies for automation use and countermeasures to task overload and workload breakdowns have also been provided.

[1]Although technically a flight training device, for simplification it will be referred to as a "simulator" in this report.

## INTRODUCTION

The development and production of personal jets such as entry level jets (ELJs) and very light jets (VLJs) have made a wider range of operations and missions available to private and professional pilots alike. Private, corporate, and charter pilots can now fly higher and faster than ever before. These jets, as with some of their slightly larger brethren, are typically certified for single-pilot operations as well as for operation by crews of two pilots. The automation and advanced technology aboard these aircraft are essential features that make flight by single pilots possible.

However, automation and advanced technology are not a panacea. The design of glass cockpit systems currently used in these aircraft places a heavy cognitive load on the pilot in terms of long-term, working, and prospective memory; workload and concurrent task management; and developing correct mental models as to their functioning (Burian & Dismukes, 2007, 2009). These cognitive demands have been found to have a direct relationship to pilot errors committed during flight (Dismukes, Berman, & Loukopoulos, 2007). Burian (2007) found a significant correlation between poor workload and time management (i.e., poor crew and single-pilot resource management, which are abbreviated CRM and SRM, respectively) and problems using advanced avionics. Additionally, almost two-thirds of the accident reports she analyzed involved at least one of six different cognitive performance problems (e.g., distraction, memory problems, risk perception). She found that these problems were experienced at similar rates by pilots flying professionally and those flying for personal reasons.

Thus, workload management is a crucial aspect of SRM. Best practices for single-pilot flight task and workload management must be better understood within the current operating environment and beyond, as we move to an era of optimizing the National Airspace System as outlined in NextGen concepts (FAA, 2012). The accessibility of these ELJs to owner-operators, who may fly less frequently than professional pilots, compels an examination of their proficiency in task and workload management, in addition to that demonstrated by professional pilots who fly these jets more regularly (National Business Aviation Association, 2005).

### Jet Single-Pilot Workload

An individual has to dedicate finite cognitive and physical resources towards performing any given task. Some of these resources include visual and auditory attention, working memory, and vast stores of declarative and procedural knowledge stored in long-term memory (Anderson, 2000). Higher order cognitive processes such as decision-making and reasoning will be required for determining strategies to properly prioritize and perform tasks. Energy is also required to perform tasks, both mental and physical. Cognitive resources have been conceptualized in various ways, including as a singular shared resource or as multiple resources dedicated to specific modalities, such as vision or hearing (Wickens, 2008).

Workload can also be associated with interrupting discrete tasks that take resources away from ongoing tasks. Within aviation, there are a number of discrete tasks that can interrupt the ongoing tasks associated with the aviate-navigate-communicate (ANC) task prioritization scheme. When individuals perform a visually-intensive interrupting task, such as searching their surroundings for obstacles or inbound traffic, they have fewer cognitive resources to attend to ongoing tasks such as navigating along a predetermined flight path. When ATC contacts an aircraft and provides a reroute instruction, that interruption requires that pilots devote auditory resources as they listen and reduces available visual resources as they write down the new clearance. When programming the new route, pilots' visual resources are narrowly allocated toward the multifunction display (MFD), and memory resources are taxed as they recall the procedure for inputting new waypoints.

The constant stream of interrupting and ongoing tasks requires that pilots shift attention among them in an intricate dance commonly referred to as multitasking or concurrent task management (Chou, Madhaven, & Funk, 1996; Hoover & Russ-Eft, 2005; Loukopoulos, Dismukes, & Barshi, 2003). However, when performing multiple tasks there is a decrement in performance caused by the time required to switch between tasks (Gopher, Armony, & Greenshpan, 2000). Pilots must recall what other tasks are waiting to be performed or where they left off when returning to an interrupted task. Thus, research has found a tendency to delay switching tasks because of the challenges involved (Wickens & Hollands, 2000).

In modern crewed operations, two pilots divide the workload between them. One pilot may be managing the entry of waypoint information, while another is communicating with ATC. The result is that fewer cognitive resources are drawn from any single crew member. In single-pilot operations, however, all of the workload must be managed alone. Part of the workload management task for the single pilot is to determine how to best use outside resources, such as cockpit automation, to help complete flight tasks (Burian & Dismukes, 2007, 2009). As described below, cockpit automation is a boon to the single pilot in accomplishing many flight tasks but one that comes with a cost. Pilots must first tell the automation what to do, through programming, and then carefully monitor it to make sure it does what the pilot intended (Roscoe, 1992).

At first, it might seem reasonable to conclude that the addition of advanced technology liberates the pilot by taking over the role of a second pilot. However, the automation that is currently available is unable to completely fulfill that role. Automation generally cannot recognize when an error has been made, respond to ATC instructions, reset the altimeter, and it cannot recognize when the pilot needs assistance. Single-pilot operations, therefore, introduce a single point of failure in an aircraft (Deutsch & Pew, 2005; Schutte et al., 2007).

### Approaches to Measuring Workload

The study of workload has resulted in the development of several instruments and measures. Often these instruments measure one's perception of how difficult a particular task is to perform. The information gained can be used with other, less subjective, data to improve training, procedures, or device interfaces to reduce workload.

One of the most well-known instruments is the NASA Task Load Index (Hart & Staveland), more commonly known as the NASA-TLX or simply, TLX. The TLX is an instrument that originally had two main steps. The first assesses the perceived difficulty of a task along six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level. The second component weights the importance of each subscale to account for individual differences to compute a final TLX score (Hart & Staveland, 1988; Hart, 2006). Over the years, the TLX has been implemented in a variety of ways. One of the variations has included using the unweighted scores for each of the subscales, thereby eliminating the need to complete a secondary rating scale. The result simplifies the analysis procedure for the researcher and makes the scale easier to complete for the respondent without sacrificing measurement sensitivity. This approach is referred to as Raw TLX, or simply, RTLX (Byers, Bittner, & Hill, 1989; Hart, 2006; Miller, 2001).

Another subjective measure of workload is the Instantaneous Self-Assessment (ISA) technique (Castle & Legget, 2002). The ISA, unlike the TLX, is a unidimensional measure of workload. ISA measures consist of a rating on a scale of one (low) to five (high) of the perceived level of workload, as well as the respondents' reaction time to provide the rating. The ISA has the advantage of being quick to administer and is minimally intrusive, unlike the TLX (Castle & Legget, 2002; Farmer & Brownson. 2003; Miller, 2001).

Cognitive Task Analysis (CTA) is an amalgam of techniques to assess performance for a task or set of tasks. CTA commonly uses direct observation of behaviors of interest, as well as interviews to glean information about the behaviors or thought processes of individuals while they attempt to perform a task (Clark, Feldon, vanMerrienboer, Yates, & Early, 2008).

**Automation Use**

The amount and sophistication of technology in aircraft have increased dramatically over the past few decades, and it is important to understand the varying roles that advanced automation, in particular, can play. First, it can act as a substitute, replacing a function the human operator would normally perform. Such is the case when an autopilot controls pitch and roll and flies a holding pattern, and when automation calculates descent points, rates, and speeds, assists with fuel management, and performs wind corrections (Casner, 2003; Hinton & Shaugnessy, 1984). Second, it can play the role of an augmenter by providing active assistance to the pilot's actions in the form of envelope protection. Third, automation can aid pilots by collecting, integrating, and presenting information about aircraft systems, airspace, traffic, and weather. For a successful flight, pilots must be able to delegate tasks to automation to reduce their own workload so that they may free up time and cognitive resources to focus on tasks that require higher-level thinking and decision making (Palmer, Rogers, Press, Latorella & Abbot, 1994).

Although there are many benefits to introducing advanced automation into general aviation cockpits, it is not without drawbacks (Aircraft Owners and Pilots Association, 2007). The automation will only do what it is programmed to do, including fly the aircraft into the ground. There are many cases of this in general and commercial aviation. For example, a Beechcraft A-36 Bonanza crashed outside of Chapel Hill, N.C., after the pilot was unable to turn the autopilot off and subsequently impacted terrain while trying to perform an emergency landing with full nose-down elevator trim (NTSB, 1992). The investigation revealed that the pilot would have been required to apply 45 lbs. of aft stick force, necessitating the use of both hands, to counteract the nose-down trim forces of the autopilot and maintain level flight.

It is also crucial that pilots constantly monitor the automation to ensure it is doing what is intended. In addition, pilots need to know what to do if the system is not performing as desired. Sometimes the pilot makes a programming error and the corrective action involves entering in the proper programming (i.e., re-programming). In other situations, abnormal or emergency procedures exist that the pilot must remember and/or access. In the Chapel Hill accident, a procedure to counteract a runaway trim/autopilot malfunction existed and could have likely prevented the fatal accident. In this circumstance, however, the pilot may not have had time or been able to physically access the procedure while struggling with an autoflight system that would not disconnect. Stress may also have impaired his ability to recall that the procedure was even available.

Modern glass cockpits in general aviation aircraft are able to present more information in the same amount of space than traditional round dial gauges. They also integrate information related to aircraft control, communication, and navigation (Air Safety Institute, 2012; NTSB, 2010), as well as allowing easier monitoring of systems, more efficient flying, and improved situation awareness (Billings, 1997; Zitt, 2006).

Although glass cockpits and automated systems are able to provide large amounts of information and assist in flying the aircraft, many suggest that pilot workload has not decreased; it has simply changed in nature (Hoh, Bergeron, & Hinton, 1983; Howell & Cooke, 1989; Wiener, 1988). For example, the pilot's task has shifted from total active controller of the aircraft to supervisory controller over the automated systems, which requires that the pilot know how the automated system operates in order to be able to understand, predict, and manipulate its behavior (Sarter, Woods, & Billings, 1997). If the automated systems suggest a potentially dangerous action, it is important that pilots are able to recognize and disregard the suggested action. Layton, Smith, and McCoy (1994) found that computer generation of a suggestion or recommendation significantly impacted the operator's decision even if, unbeknownst to the operator, the recommendation was poor and had potentially harmful consequences.

Increased cognitive workload with higher levels of automation may be a function of an increasing memory burden, with pilots having to remember how and what the machine was programmed to do and what it is supposed to be doing over long periods of time. Increasing memory burden requires pilots to use prospective memory, in which they must remember to remember when to perform a task whose execution must be delayed. In the meantime, unrelated tasks are performed, which increases the possibility that pilots will forget to complete the delayed task when it is time to do so (Dismukes, 2010). Furthermore, although automated systems are able to perform procedural and predictable tasks, it is the human operator who is ultimately responsible for tasks requiring inference, judgment, and decision making. When pilots get overloaded with information, their situation awareness, judgment, and decision making become impaired (Burian & Dismukes, 2007).

*Mode awareness* is the ability of an operator to track and anticipate the behavior of an automated system (Sarter & Woods, 1992). A moded system is one that produces different behaviors depending on which mode is currently in use (Casner, 2003). A major factor in the safe use of automation lies with the operator knowing what is happening and why. Pilots must be able to evaluate the automation's intentions through its actions and performance. Mode errors typically occur because the automation interface fails to provide the user with salient indications of its status and behavior (Sarter & Woods, 1995). It is important for manufacturers of airplanes with glass cockpits to ensure that pilots are provided the necessary cues to understand what mode is in use and how to address issues pertaining to possible mode confusion (GAMA, 2005).

The design of modern glass cockpits must take into account how many buttons are feasibly able to be placed on the glass panel and how many different layers of menus within those buttons can be used until the pilot becomes confused (GAMA, 2000, 2005). With glass cockpits having layered menus and softkeys that do different things depending on previous button presses, there is a greatly increased demand on memory and attention (Burian & Dismukes, 2007). An NTSB (2010) report on the introduction of glass avionics found that complex integration of data and confusion caused by multiple display modes are some of the leading causes of glass panel accidents.

With increased levels of automation, it is vital that pilots avoid becoming complacent in the cockpit and are constantly ensuring that the system is providing the desired action. Wiener (1981) defines complacency as a psychological state characterized by a low index of suspicion that results from working in highly reliable automated environments. It has been established that automation use can lead to complacency in monitoring and a decrease in mode awareness (Parasuraman, Molloy & Singh, 1993; Sarter & Woods, 1995). There is also evidence for the role of personality in automation use as well. In a study conducted by Prinzel (2002), it was demonstrated that self-efficacy (i.e., the belief in oneself as competent and capable) is a moderating variable when identifying pilots who are likely to succumb to automation-induced complacency. Those with low self-efficacy were more likely to suffer from complacency-induced errors.

### The Current Report

This report focuses on ELJ single-pilot workload strategies and performance during four high workload events that occurred during the climb out and en route portions of flight. Performance was evaluated against airline transport pilot and instrument rating practical test standard criteria (FAA, 2008a, 2010), as well as the successful completion of the scripted tasks. Because this was an exploratory study, instead of developing a number of detailed hypotheses to test, we designed situations that we believed would increase workload and embedded them in experimental scenarios for our study participants to fly. These scenarios involved flight in the relatively demanding operational environment of the U.S. east coast corridor from the New York City area through and to the southwest of Washington, DC. We were interested in learning about how single-pilots flying an ELJ manage their workload and use automation in such an environment. We were interested in examining problems they encountered, determining possible reasons why, and identifying strategies for task management and automation use that worked out particularly well (i.e., "best practices"). We also wished to gather baseline information on single-pilot operational behavior for reference in future studies. The data from the current study provided an opportunity to begin constructing a model of normative behavior and workload management strategies involved in single-pilot jet operations.

## METHODS

### Participants

The FAA Airmen Certification Branch provided the names of all pilots who possessed a C510-S type rating at the time of our request. From that list, 321 pilots were identified as living in the contiguous 48 United States of America. These pilots were mailed recruitment letters briefly describing the study and invited them to contact the NASA Ames Human Systems Integration Division Testing and Participant Recruitment Office if they were interested in participating. One hundred one pilots responded and were sent, via email, a copy of the NASA Informed Consent form and three questionnaires: Demographics, Advanced Avionics and Automation, and Schedule Availability. Forty-six pilots (3 females and 43 males) returned the completed questionnaires, and 14 male pilots were selected for participation in the simulation portion of the study. Participation in the study was voluntary, and pilots were allowed to terminate their participation in the study at any time, though none chose to do so. They were paid a rate of $50.00 per hour of participation and were reimbursed for all travel costs and provided a per diem for the cost of meals.

### Materials

***Demographic questionnaire***. Background information was solicited from potential participants to screen for pertinent flight certification and history that was essential for the study. A portion of this information was used to identify potential participants representing the population of interest (Mustang owner-operators), as well as others (i.e., professional pilots) who flew the experimental scenarios in the simulator. In addition to the type of flying performed and hours of experience, participants were asked to rate their experience and perceived skill levels regarding the use of various avionics packages and cockpit technologies such as the Garmin G1000™ and autoflight systems. As indicated earlier, 46 participants completed the demographics questionnaire, which can be referenced in Appendix A.

***Advanced avionics and automation questionnaire***. An advanced avionics and automation questionnaire was also completed by 46 participants. This questionnaire was designed to gather information with regard to participant attitudes toward advanced technologies such as glass cockpits/primary flight displays and multifunction displays. The participants were polled on which features they preferred most and least, as well as on issues related to advanced avionics and automation design, functionality, use, training, and maintaining proficiency, among other things. The questionnaire can be found in Appendix B.

***Citation Mustang and G1000 Cockpit Set-up Preferences questionnaire***. The 14 pilots who participated in the simulator portion of the study completed a questionnaire to indicate their preferred Garmin G1000 default settings. This information was then used to set up the G1000 in the study simulator prior to their session to match those settings in the actual aircraft that they flew. For example, temperatures on the G1000 displays can

be expressed in degrees Celsius or degrees Fahrenheit. Similarly, pilots can choose among 12 different variables, such as distance (DIS), estimated time of arrival (ETA), and true airspeed (TAS), for display in four fields at the top of the G1000 Multifunction Display (MFD). The Citation Mustang and G1000 Cockpit Set-up Preferences questionnaire can be seen in Appendix C.

***Flight bag materials***. A flight bag was provided for pilots to use during their flights in the simulator. Items in the flight bag included a knee-board with paper; pencils and pens; three different types of flashlights; colored sticky tabs; a stopwatch/timer; a baseball cap; current Visual Flight Rules (VFR) sectional and terminal charts; current paper Jeppesen high and low altitude Instrument Flight Rules (IFR) en route navigation charts; complete Jeppesen Airway Manuals with current paper departure, arrival, and approach plates; and current Airport and Facilities Directories. Pilots were allowed to take as much or as little of the flight bag materials with them into the simulator as desired. However, once the scenario began, pilots were not allowed to leave the simulator to retrieve flight bag materials they had left behind in the pre-flight briefing room.

***Flight briefing materials***. Prior to each scenario, pilots were provided with a binder of briefing materials (see Appendix D). Each binder included:

- The purpose of the flight, airports of departure and destination, the current date, proposed time of departure, aircraft location on the field at the departure airport, and planned aircraft parking at the destination airport
- A departure airport diagram (downloaded from the Web) with the aircraft's location indicated
- A completed flight plan on FAA Form 7233-1
- A navigation log
- Completed weight and balance information, including a weight and balance diagram
- A complete weather briefing package including an area forecast and synopsis, current satellite conditions, significant meteorological advisories (SIGMETs) and airmen weather advisories (AIRMETs), weather and sky conditions, pilot reports (PIREPs), meteorological aerodrome reports (METARs), and terminal area forecasts (TAFs) and radar returns for departure and destination airports, winds aloft forecast for the route of flight, en route METARs and terminal area TAFs, and a complete set of notices to airmen (NOTAMs). Some of this material was downloaded (and modified as necessary) from the National Oceanic and Atmospheric Administration (NOAA) Aviation Weather Center Aviation Digital Data Service (ADDS) on a day with similar conditions as that in the scenarios (see http://www.aviationweather.gov/adds/ ).

***Familiarization and experimental flight scenarios***. With the help of a Cessna Citation Mustang and other jet pilot subject matter experts (SMEs) and in consultation with ATC SMEs, two flight scenarios were designed for use in this study. The first flight was developed so that participants could become familiar and comfortable with the research environment, including the simulator, the panel mounted eye-tracker, and the ISA measure (described below).

The familiarization flight was an IFR flight lasting approximately 30 minutes from Clinton-Sherman Airport (KCSM) in Oklahoma, to Will Rogers World Airport in Oklahoma City, Oklahoma (KOKC). Pilots performed the same flight tasks that they would complete for the experimental flight, including reviewing the pre-flight briefing packet materials, pre-flight cockpit preparation, conducting a takeoff and an instrument departure, instrument en route navigation, communicating with ATC, and completing an instrument approach and landing. Although pilots were completing an IFR flight, the weather for the familiarization flight was visual meteorological conditions (VMC). The scenario was designed to produce relatively low workload, although on two occasions the pilots were informed of traffic crossing their route of flight that was not a conflict (i.e., "not a factor") by ATC. Following the familiarization flight, the participants were asked if they had any questions and if they understood how to use the ISA device. No data from the familiarization flights were analyzed. Figure 1 illustrates the route of flight for the familiarization scenario.

The experimental flight consisted of two legs, each approximately one hour in length. Each leg was designed to include a number of high workload tasks that would be typical of the type experienced by pilots flying along the scripted routes. In the first leg, pilots departed from Teterboro

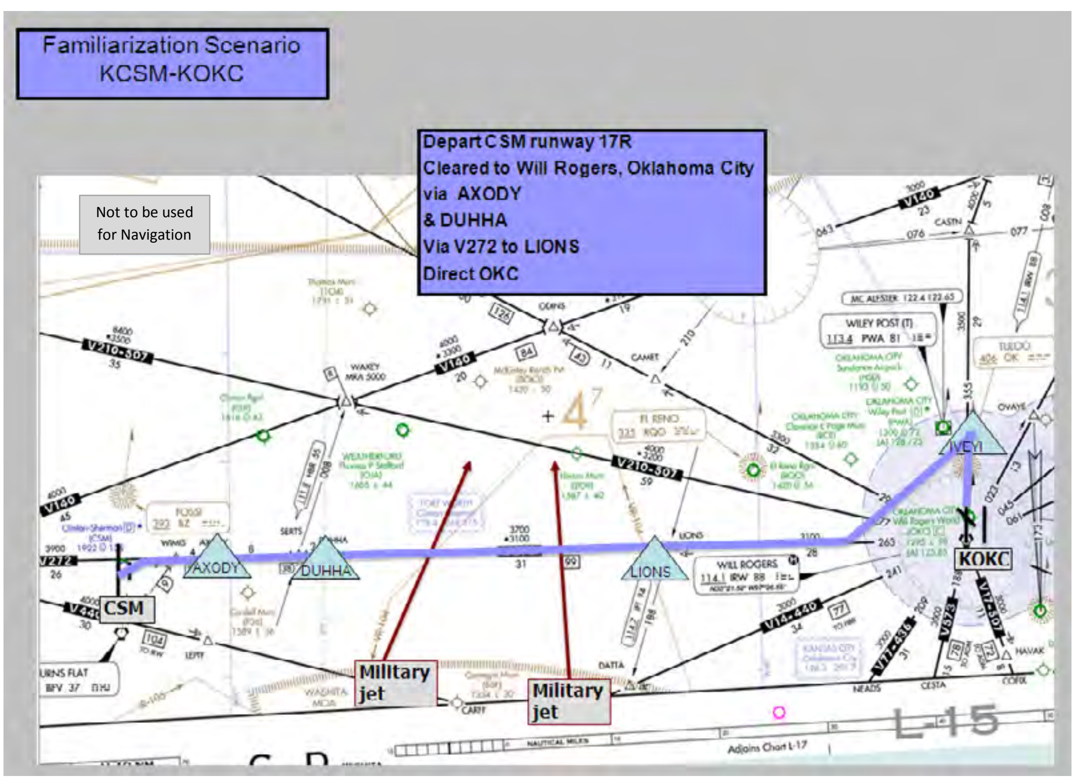



*Figure 1.* Familiarization Scenario Route of Flight.

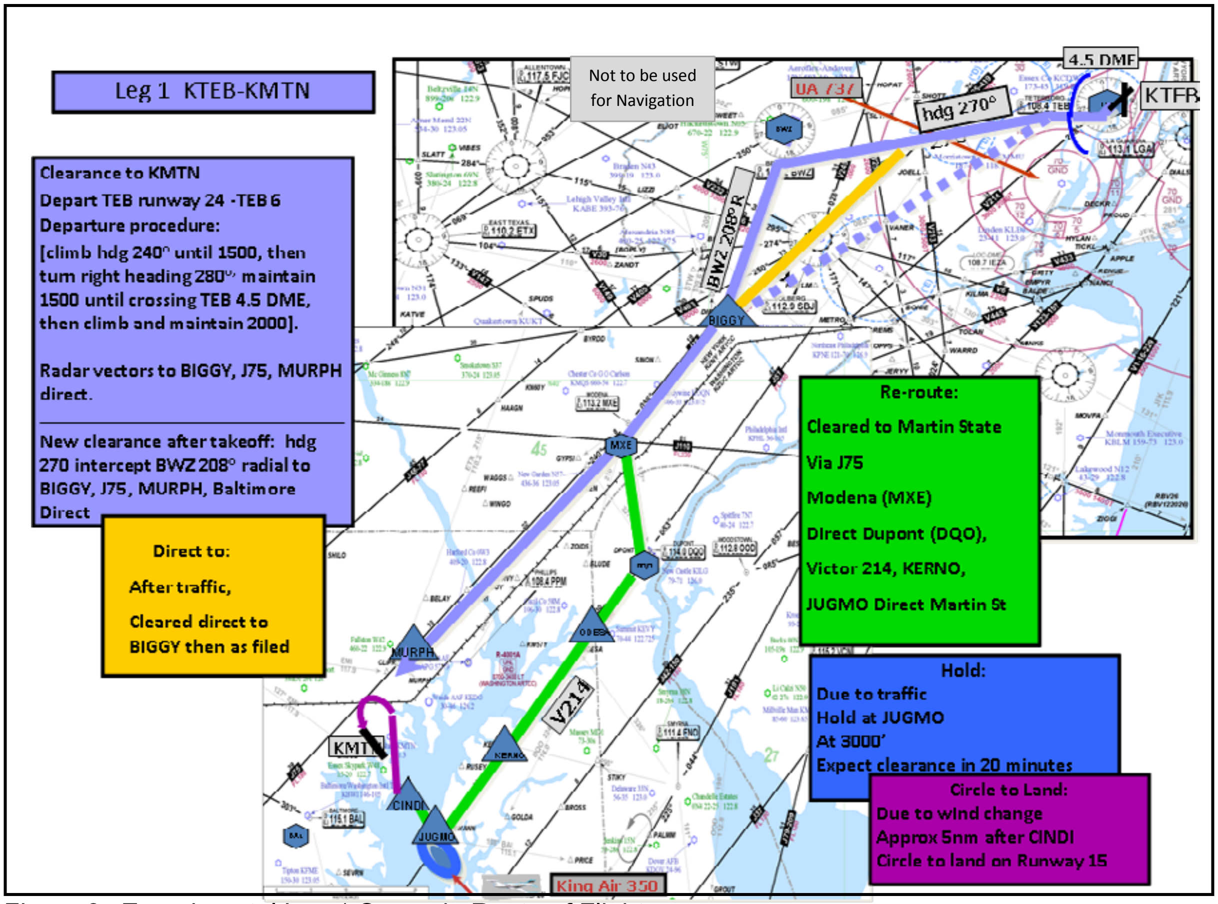



*Figure 2.* Experimental Leg 1 Scenario Route of Flight.

Airport in New Jersey (KTEB) and landed at Martin State Airport (KMTN) just outside of Baltimore, Maryland. In addition to normal piloting tasks such as reviewing briefing materials and conducting en route navigation, the participants were confronted with the following high workload tasks and conditions:

- TEB6 Departure off runway 24, KTEB
- Intercept the Broadway (BWZ) 208° radial
- In-flight reroute
- Meet a crossing restriction at a waypoint
- Hold at a waypoint
- RNAV (GPS) Rwy 33, circle to land Rwy 15 at KMTN
- IMC conditions throughout, although not down to minimums and no convective weather
- Traffic, although none was intended to be a factor for the participant pilots

After a break for lunch, lasting 30-60 minutes, pilots then completed the second leg of the experimental flight in which they departed from Martin State Airport (KMTN) for a destination of Hot Springs/Ingalls airport (KHSP) in Virginia. The high workload tasks and conditions of this leg included:

- Radar vector departure from KMTN
- Expedited descent to accommodate another aircraft with an emergency
- The pop of the anti-skid circuit breaker approximately half-way through the scenario
- Meet a crossing restriction 15nm prior to a waypoint
- Asked to assist in relaying communication to a Washington Center controller from a lost pilot at the same time as meeting the crossing restriction and preparing for the approach and landing
- Perform the ILS or LOC Rwy 25 approach at KHSP
- Deal with a temporarily disabled aircraft on the runway at KHSP (typically by going around or performing the missed approach procedure)
- IMC conditions throughout, although not down to minimums and no convective weather
- Traffic, although none was intended to be a factor for the participant pilots with the exception of the disabled aircraft at KHSP

Figures 2 and 3 illustrate the route of flight and major workload tasks for the experimental flight Legs 1 and 2, respectively.

***Background chatter***. An essential part of pilot workload in busy airspace is attending to background chatter on the radio, in part to monitor for a call from ATC but also to be alert to surrounding aircraft activity in case there might be some effect upon one's own flight. An elaborate script of background chatter involving over 100 other aircraft was developed and recorded for use in this study (Burian, Pruchnicki, & Fry, 2013). Unfortunately, unanticipated problems were experienced with the simulator audio system and we were unable to use it. We did, however, have a few occasions where "other pilots," such as the "lost pilot" during the second leg of the experimental flight, interacted with ATC and with the study pilots over the radio during the three scenarios.

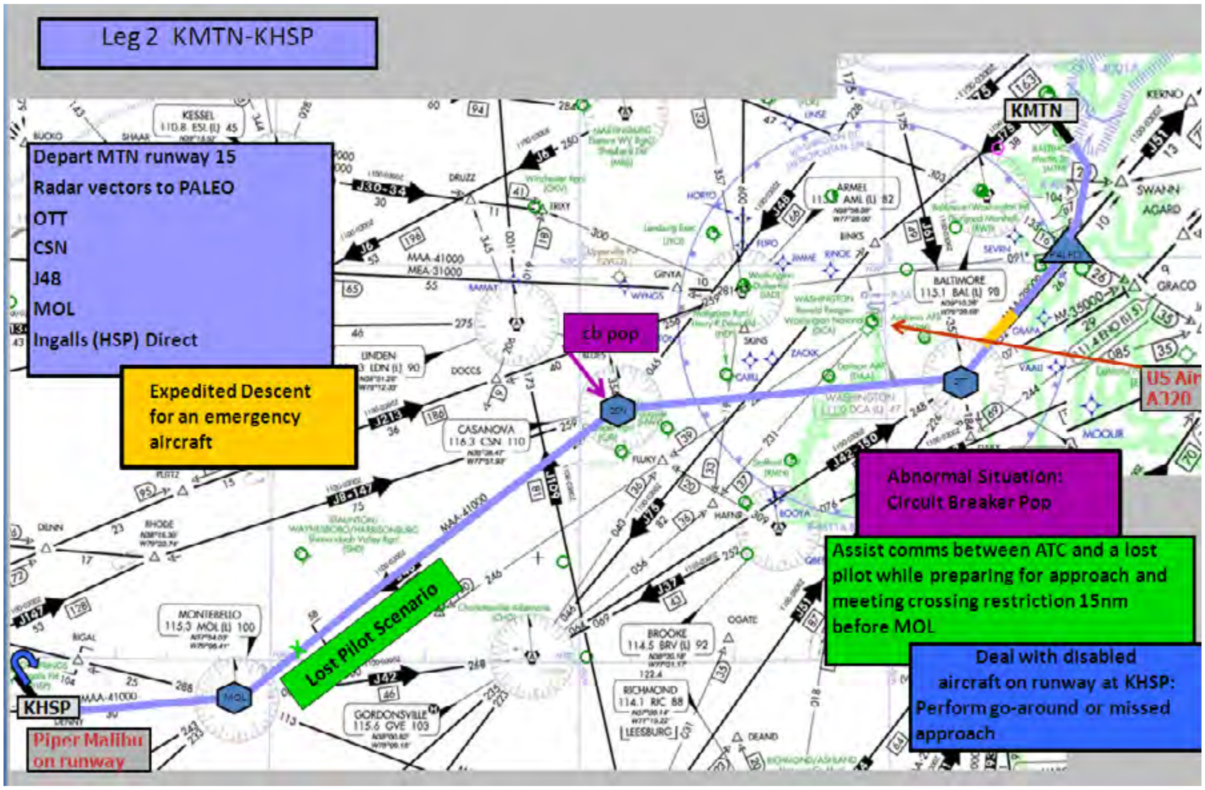



*Figure 3.* Experimental Leg 2 Scenario Route of Flight.

All "other pilot" communications were scripted and performed by members of the research team in real time (i.e., not pre-recorded) as the scenarios unfolded.

***Study scripts***. Detailed scripts were developed for all three study scenarios and were used to guide all communications from ATC and other pilots as well as the triggering of all events, such as the circuit breaker pop during the second leg of the experimental flight. The scripts included the following: aircraft location, active radio frequency, triggers for all ATC calls to the participant pilots (such as the aircraft's location), notes and alternate actions that may be necessary, a description of pilot tasks (to facilitate situation awareness among the ATC and researchers), and all exact communications from ATC and other (non-participant) pilots.

**Familiarization Flight - Comms**

| Aircraft Location | Active Radio Freq. | Trigger | Alternate/ Notes | Pilot Task | ATC/ Flight Watch Comms | Mustang Pilot (Study Participant) Comms | Other Pilots - Live Comms | Recorded Comms (ATIS, AWOS, Background Chatter) |
|---|---|---|---|---|---|---|---|---|
| AXODY, climbing to 11,000 ft. | 128.4 (Fort Worth Center) | Aircraft is at AXODY | | Respond to ATC Traffic Call | "Citation 510C You have crossing traffic at 4000, right to left, 2 o'clock and ten miles, a Citation Sovereign." | | | |
| | | | exact comms will vary depending upon if pilot sees traffic | | | (pilot acknowledges traffic call - looks for traffic) | | |
| | | | | | "Sovereign 36V, You have crossing traffic at **XXXX** feet climbing, crossing left to right 10 o'clock and ten miles, a Citation Mustang" | | | |
| | | | | | | | 36V has traffic | |
| | | | | monitor level off at 11,000 ft | | | | |
| **Cruise** | | | | | | | | |
| on assigned route, 11,000 ft. | | Aircraft is 15 nm before LIONS | | Respond to ATC Traffic Call | "Citation 510C You have crossing traffic at 8000, right to left 2 o'clock and five miles, an A320" | | | |
| | | | exact comms will vary depending upon if pilot sees traffic | | | (pilot acknowledges traffic call - looks for traffic) | | |
| | | | | | "Frontier 1449, you have crossing traffic at 11,000, left to right at 10 o'clock and 4 miles, a Citation Mustang" | | | |
| | | | | | | | "Lookin' for the little fella, Frontier 1449" | |
| | | | | | | | | Will Rogers Oklahoma City Airport Information BRAVO 1655 Zulu automated weather, wind is 230 at 5 gusting to 14, visibility 10 miles, 25,000 few, temperature 30, dew |

*Figure 4.* Excerpt of the Familiarization Scenario Script.

An excerpt of the familiarization scenario script can be seen in Figure 4. All of the scripts developed for this study are included in their entirety in Burian, Pruchnicki, and Fry (2013).

***Cessna Citation 510 Mustang flight simulator***. The flight simulator used in this study was a Frasca level 5 flight training device that features a realistic Mustang flight deck with a G1000 avionics suite, digital control loaders, and a high-fidelity digital surround sound system that accurately replicates flight, engines, system, and environmental sounds. The out-the-window (OTW) display system included a 3D Perception 225 degree (lateral angle) spherical projection screen that gave the pilot a realistic field-of-view.

Six wide-quad-extended-graphics-array (WQXGA) (1920x1200) projectors were driven from six high-end Intel server class computers at 60 Hz. The projection screen used embedded sensors to detect the alignment, brightness, and edge blending quality of the projected images. The projection system was used to display high-fidelity MetaVR™ terrain imagery and 3D computer models of the airports that the pilots would encounter during the study. Pictures of the simulation environment can be seen in Figures 5 and 6.

***Eye tracker***. Eye movements of participants were tracked using a FaceLab™ v5 system consisting of non-invasive cameras, IR emitters, and software from Seeing Machines, Inc. Camera set-up and calibration procedures were followed, as described in the FaceLab user manual, except where modified for use in the simulator cockpit. Specifically, the dual eye tracking cameras were mounted on the left-seat cockpit dash, above the level of the control yoke column without blocking the view of either the outside or the cockpit instruments. In addition, during calibration procedures, the pilot (rather than the experimenter) held the calibration target up to the camera while seated in the cockpit to ensure that the distance to the cameras were consistent and tailored for each pilot's height and seating position. Image quality, camera focusing, and calibration were confirmed by the experimenter on a computer laptop located just outside and below the left cockpit window and initially required 10-15 minutes. Recalibration of the eye-tracker took only a minute or less and was performed every time the participant re-entered the simulator cockpit following a break.

Due to calibration errors, events in the simulated flight could not be related to tracked eye movements in a manner required for monitoring time-dependent cognitive workload; therefore, analysis of the eye tracking data was not possible. It is recommended that a system of video and audio time-event markers, called "time hacks," be included in future eye tracking/flight simulator studies.

*Figure 5.* Cessna Citation Mustang Flight Simulator and Projection System.

*Figure 6*. Simulator G1000 Avionics Suite and Out-The-Window View.

Table 1. Experimental Flight ISA Rating Prompts.

| Leg 1 | Leg 2 |
|---|---|
| 2000 foot level-off plus 60 s | Aircraft reaching 2000 feet plus 60 s |
| Heading change for BIGGY waypoint plus 60 s | Aircraft reaching 6000 feet after expedited descent |
| Reaching COPES waypoint | Aircraft reaching FL200 plus 60 s |
| Initiation of descent from FL200 | Aircraft turning over CSN VOR plus 60 s |
| Aircraft descending through 12,000 feet | Aircraft reaching MOL VOR |
| Aircraft turns outbound after crossing JUGMO waypoint in the hold | Aircraft turning inbound over AHLER waypoint on the approach plus 15 s |

Table 2. Experimental Flight NASA TLX Task Rating Events.

| Leg 1 | Leg 2 |
|---|---|
| Leg 1 Flight Overall | Leg 2 Flight Overall |
| KTEB 6 Departure | KMTN Departure |
| Build Course to Intercept Broadway (BWZ) 208 Radial | Immediate Descent for Emergency Aircraft |
| VNAV Path to Descent | Circuit Breaker Pop Event |
| Hold at JUGMO Waypoint | Assist Lost Pilot |
| RNAV (GPS) Rwy 33 Approach and Circle to Land Runway 15 KMTN | Meet Crossing Restriction Before MOL VOR |
| | ILS Approach to KHSP |
| | Deal With Disabled Aircraft and Complete Landing at KHSP |

***Instantaneous self-assessment (ISA).*** The ISA device consisted of a small rectangular box with a red light at the top and five numbered buttons arranged vertically below it. Pilots were prompted to perform an instantaneous self-assessment of workload by pressing one of the five numbered buttons (with 5 being associated with "very high" workload and 1 meaning "very low" workload) when the red light was illuminated. Researchers controlled when the light would illuminate remotely from the experimenter's station. Once illuminated, the light would stay on for up to 60 s or until the participant pressed one of the numbered buttons. Prior to the familiarization flight, pilots were briefed on the use of the ISA rating system and were provided a printed card, retained for their reference during flight, which reiterated how the ISA was to be used and described the meaning for each ISA rating. Pilots were also informed verbally and in writing that making an ISA rating when prompted was secondary to any other task. They were instructed to only make the rating when they were able and to not make a rating at all if there was no break in their primary task during the 60 s that the ISA light was illuminated. Table 1 depicts checkpoints where participants were prompted to make an ISA workload rating during the two legs of the experimental flight.

***NASA Task Load Index.*** Paper and pencil versions of the NASA TLX were administered immediately after Leg 1 and again after Leg 2. Pilots were asked to give ratings on each of the subscales for the flight overall, as well as for specific high workload tasks or phases of flight. The events for which participants completed a TLX for both legs of the experimental flight are shown in Table 2.

***Data acquisition and storage.*** The Cessna VLJ Mustang simulator lab used three systems to digitally record and store audio, video, and simulator data streams. Each stream was recorded and analyzed independently. All data recording systems were managed and controlled at the operator station.

***Audio recordings safe***. A Zoom H4n Handy Recorder™ was used to record and store high-fidelity audio recordings of cockpit, ATC, and experimenter communications as well as post flight interviews that were conducted with each participant. The Zoom H4n Handy Recorder stores audio information in 96Khz, 24-bit, MP3 digital audio files onto standard Secure Digital High Capacity (SDHC) memory cards. Additional audio recordings of pilot and ATC communications were achieved through a high-fidelity digital recording system which employed several devices that were networked together. These audio recordings were integrated into the video recordings, discussed below.

***Video recordings***. Four Arecont Vision IR™ video cameras were specifically selected for their high resolution color image streams. Two of the Arecont cameras were mounted on tripods placed on each side of the simulator cockpit. The camera on the pilot side recorded the pilot's primary flight display (PFD). The camera on the co-pilot side recorded the pilot so participant well-being could be monitored as required by FAA and NASA Institutional Review Board protocol. A third camera was mounted at the aft of the simulator cab to record the MFD. The fourth camera was mounted inside the cockpit on the co-pilot's window pillar, and it recorded the co-pilot's PFD. All four cameras operated at 60hz NTSC signal and were infrared (IR) sensitive.

A Plexsys™ data recording system called Enhanced Mission Record and Review System (EMRRS™) was used in the VLJ simulator lab to record, process, and store high-quality digital video streams. EMRRS was used to combine multiple audio, video, and data streams and store them on a Plexsys media storage server. The Arecont Cameras and sound mixer were connected to the Plexsys recording system through a network hub. EMRRS synchronized all the recorded streams for accurate time-stamped playback and real-time analysis. Additionally, it provided real-time observation of pilot activity during the recording, including pausing, rewinding, and replay of the media without disturbing the recording.

***Simulator data stream***. The Frasca simulator features a data storage capability including 5159 variables. The variables are a recording of the state of the aircraft and the immediate simulated environmental conditions. The data are stored in a Frasca proprietary file format that is exported to standard, comma delimited, or comma separated value (CSV) text files, which can be opened in a variety of spreadsheet programs.

***Experimenter's station***. Researchers and air traffic controllers sat at the experimenter's station (see Figures 7 and 8) situated approximately 20 feet behind the simulator. Several monitors at the station allowed the researchers and ATC to monitor the progress of the flight and the feed from the video recorders in the cockpit. Researchers playing the role of "other pilots" and ATC wore headsets at the station and spoke on the radios by pressing a push-to-talk switch on the headset or audio system panel.

***Pilot headsets***. Pilots were invited to bring and use their own headsets but none did. The simulator came with a set of lower-quality foam headphones that are not noise-cancelling. They were used by one participant and resulted in some difficulty in hearing ATC communications. All the remaining participants used a Bose A20 noise-cancelling headset that we provided.

*Figure 7.* Experimenter's Station. The Simulator and Visual System can be Seen in the Background.

*Figure 8.* Researchers and ATC at the Experimenter's Station.

***Debriefing interview***. After a short break following the second leg of the experimental flight, a semi-structured debriefing interview of participants was conducted. We asked pilots about their overall impression of their experience for the day and if there were any tasks performed during the flights that increased their workload. In addition, we asked how they felt they managed their workload during the flights. For a complete description of the specific questions that were asked during the semi-structured interviews, see Appendix E. These interviews were recorded as WAV files on a digital audio recorder and were transcribed for later analysis.

***Task analyses***. During the study design phase of this research, high level outlines of the two experimental flights were constructed (Burian, Christopher, Fry, Pruchnicki, & Silverman, 2013). These outlines included all the major tasks to be completed by the participants during those flights. Detailed tasks analyses were then conducted with the assistance of a SME who is knowledgeable about the G1000 and serves as an instructor and mentor pilot in the Cessna Citation Mustang. In these task analyses, the major tasks were broken down into subtasks, sub-sub-tasks, and so on until each step for the completion of a task was identified down to the level of pressing a button or turning a knob. To the extent possible, cognitive tasks associated with some of these physical tasks (e.g., "recall that ATC gave direction to report when reaching assigned altitude") were also included. These task analyses were developed to classify the correct way in which each task must be completed or—when multiple ways of accomplishing a task exist—classifying one way of accomplishing the scripted tasks that represents the correct action and a superior approach to workload management and task completion, as determined by our SME. The task analyses were used during data analysis when reviewing approaches to task completion and workload management employed by the study participants. The task analyses for the two experimental flights can be seen in their entirety in Burian et al. (2013).

***Concurrent task timelines***. Following the completion of the task analyses for the two experimental flights, we developed Concurrent Task Timelines (CTTs) in which bars (or lines) representing the first three levels of tasks and sub-tasks included in the analyses were drawn relative to each other (the horizontal axis on the page indicates time; see Figure 9). The purpose of these timelines was to depict concurrent tasks in a format that indicted their expected length relative to each other. Again, our Cessna Citation Mustang SME assisted in the development of these timelines, which were used by researchers during the data analysis phase of the study for identifying and evaluating participant performance and workload management strategies. The complete CTTs for both experimental flights can be seen in Burian et al. (2013).

## Design

This exploratory study of jet single-pilot workload management was observational in nature. As described earlier, detailed scripted flight scenarios which included a variety of typical but high workload tasks were developed, and pilots representing the population of interest agreed to fly the scenarios. Recently retired air traffic controllers who had experience directing traffic in the US northeast corridor (where the experimental flights took place) were hired to play all the roles of ATC in the scenarios (e.g., ground controller, local controller, departure, center, etc.).

## Procedure

The evening before each of the participants was scheduled to complete the study, they met with one of the researchers to review the study procedures and purpose. Participants were given an opportunity to ask any questions, and they signed the FAA Informed Consent Form. They were given the flight briefing materials and associated charts and maps for the familiarization flight. Participants conducted whatever pre-flight planning they felt necessary for the familiarization flight that evening in their hotel rooms. Participants were told that they should both prepare for and fly the scenarios in the same ways as they normally did when flying in the real-world.

The following morning, participants were picked up from their hotel rooms and driven to the simulator facility at CAMI. The pilots first completed a flight around the pattern at KOKC to begin getting familiar with the simulator environment. During this circuit (on downwind), pilots were cued to read a series of words printed on a card. This provided baseline audio data for use in later analyses of pilot voice communications and workload during the experimental flight. All pilot communications in the simulator (once their headset was on) were captured in WAV files. Tail numbers of the participant's own Mustang aircraft were used during all ATC radio communications throughout familiarization and experimental flights to further a sense of familiarity for the pilots in the simulation environment.

Following the completion of the circuit at KOKC, pilots were given an opportunity to review the briefing materials for the familiarization flight from KCSM to KOKC and were provided the flight bag materials. Pilots then re-entered the simulator cockpit, were briefed on the use of the ISA, participated in the initial calibration of the eye-tracker, and flew the familiarization flight, which lasted approximately 30 minutes.

Pilots were then provided a brief break, typically around 10 minutes, and were offered a choice of beverages and snacks. They were given the briefing materials for the experimental flights and were told that they could review the materials for both

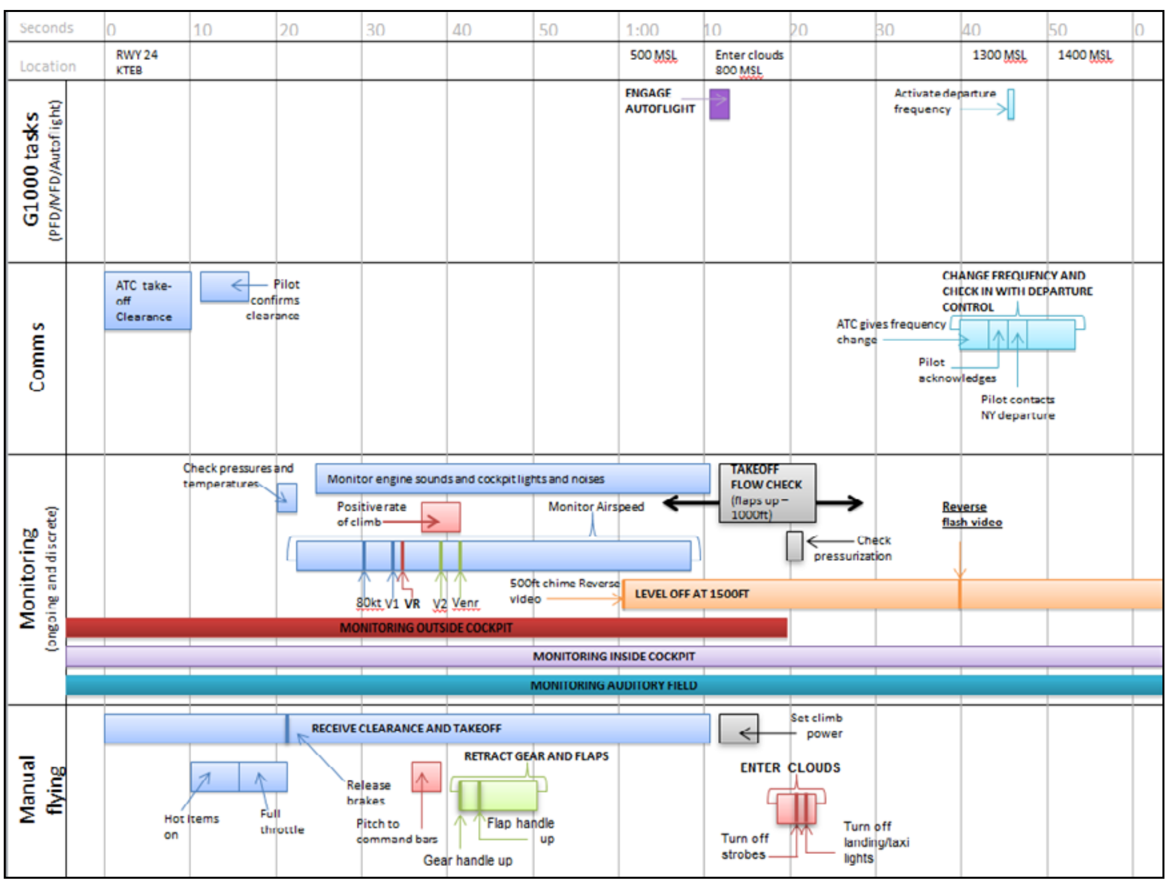



*Figure 9*. Sample Portion of a Concurrent Task Timeline.

legs or only the first, whichever they preferred. The amount of time taken by participants to complete this pre-flight briefing varied according to whether both legs or only the first leg was briefed and ranged from 12 to 90 minutes. Those participants who only briefed the first leg took approximately 30 minutes to review the materials.

When pilots expressed that they were ready, they flew the first leg of the experimental flight, which lasted approximately 60 minutes. In this flight, they departed from Teterboro, New Jersey (KTEB) with a destination of Martin State Airport (KMTN), near Baltimore, MD, during daylight hours in September on a moderate IMC day. The aircraft was fully fueled. Following cockpit setup and G1000 initialization, the flight was cleared to Martin State Airport via the Teterboro Six Departure.

An IFR flight plan was filed and the departure weather consisted of rain and a slight crosswind at KTEB. Due to proximity to New York City, the departure procedure was complex. IMC was encountered during the initial climb. Once established en route with New York Center, radar vectors and route modifications were assigned. Altitude restrictions were applied as well to avoid simulated traffic conflicts in busy airspace. The flight evolved normally and was representative of a typical flight in the USA Northeastern Corridor. After handoff to Washington Center, and following a brief hold, the single pilot completed the RNAV (GPS) RWY33 non-precision approach in marginal VFR conditions and circled to land on runway 15. After landing, the participant shut down the aircraft.

At the completion of the flight, participants left the simulator, completed the NASA TLX measures for the first leg, and were then provided lunch. Following the lunch break, pilots were given an opportunity to review the briefing materials (or conduct a pre-flight briefing if not done earlier) for the second leg of the experimental flight. Participants' review of the second leg briefing material ranged from 4 minutes to 45 minutes and varied according to whether the second leg had been briefed earlier as part of the Leg 1 review. When pilots indicated they were ready, they flew Leg 2 of the experimental flight.

In Leg 2, the participants departed from Martin State airport (KMTN) with a destination of Ingalls Field at Hot Springs, Virginia (KHSP). This flight took place during daylight hours in September on a moderate IMC day. Following the cockpit setup and G1000 initialization, the aircraft was cleared to Ingalls Field via the radar vectors to PALEO, the Nottingham (OTT) VOR and then as filed. Runway 15 was in use for departure with an initial altitude assigned of 2000' MSL.

An IFR flight plan was filed for the KMTN departure and a slight crosswind existed. The departure procedure was straight out and simple, but the airspace in the D.C. Metroplex is complex. IMC was encountered during the initial climb, and altitude restrictions were applied to avoid traffic conflicts. During the climb to cruise altitude, the aircraft was instructed by ATC to descend immediately to accommodate another aircraft with an emergency. Once established en route with Washington Center, the flight evolved normally and was representative of a typical flight in the USA Northeastern Corridor. However, a relatively minor non-normal event occurred (the popping of a circuit breaker) which required reference to a non-normal procedure in the aircraft Quick Reference Handbook (QRH). In the final third of the flight, the pilot was asked to assist with communication between Washington Center ATC and a pilot who was lost and flying too low to be heard by ATC. Upon receipt of the Automated Weather Observation System (AWOS) for KHSP, the pilot was instructed to prepare for a precision ILS approach with an expected break-out from the overcast at 600 ft above decision height (DH). As part of the experimental design, an aircraft landing prior to the participant's aircraft was temporarily disabled on the runway, forcing the participant to go around or complete a missed approach procedure. Following the second landing attempt, the pilot secured and shut down the aircraft.

NASA TLX measures for the second leg were then completed, and the participant was provided a short break before participating in the debriefing interview. At the completion of the debriefing interview, participants were thanked for their participation and provided a certificate and CAMI promotional pen as thank you gifts. Participants were reminded of reimbursement procedures for their travel expenses and were driven back to their hotels.

## DATA MANAGEMENT AND PREPARATION

This report focuses on single-pilot workload management and performance during four high workload events that occurred during the en route phase of flight from the completion of the departure procedure/ initial climb to the initiation of an instrument approach procedure. We spent several months downloading and organizing data from the simulator itself, the audio and video recordings, the ISA data, and the eye tracker data. CAMI personnel placed these data on external hard drives, some of which were shipped to NASA collaborators. We also transcribed the recorded debriefing interviews conducted with participants and recorded Mustang SME comments made while reviewing the recordings of the experimental flight. We also developed and populated four databases with information from three questionnaires and NASA TLX workload measures. NASA personnel shared updated documents outlining data to be analyzed, research questions to be answered, and hypotheses to be evaluated.

Biweekly, weekly, and sometimes daily teleconferences were held among NASA and CAMI research team members to discuss data management and preparation, data analysis, findings, writing assignments (which were distributed among the team), and to edit this report. Because of the qualitative nature of much of the data and the large and distributed nature of the research teams, much more coordination and communication regarding the approach to data analysis was needed than is typically the case.

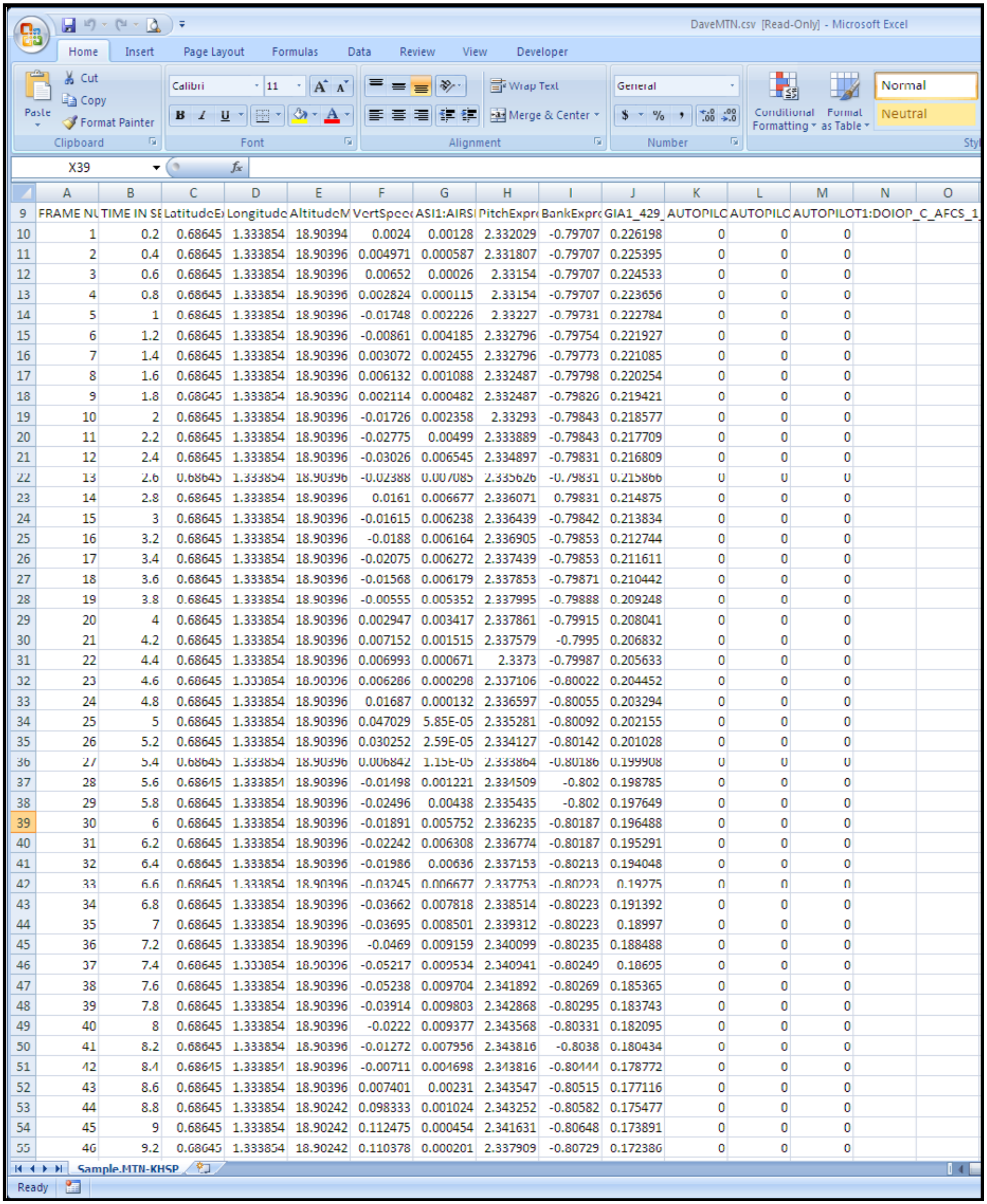
### Simulator Flight Performance Data and Data Extraction

The Frasca simulator included the capability of recording real-time flight data. The data stream contained 5,159 separate simulation variables sampled and recorded at a rate of 5Hz. Each sample constitutes a sequentially numbered "frame" in the data stream. These data included latitude, longitude, and altitude information, the status of cockpit controls and displays, simulated weather settings, aircraft attitude and airspeed, and the activation and values of specific G1000 settings (e.g., barometric pressure). Following the completion of each scenario, the simulation data stream recording was stored in a proprietary data format on the local simulator drive.

Table 3. Sample Flight Simulator Variables.

| Parameter | Units | Variable Name |
|---|---|---|
| Altitude (MSL) | Feet | AltitudeMSLExpression_Ft |
| Indicated Airspeed | Knots | IndicatedAirspeedExpression_Kts |
| Heading (Magnetic) | Degrees | MagneticHeadingExpression_Deg |
| Vertical Speed | Feet per Minute | VertSpeed_Fpm |
| Bank Angle | Degrees | BankExpression_Deg |
| Pitch Angle | Degrees | PitchExpression_Deg |
| Landing Gear Position | True or false | MISCOUTPUTS:NOSELDGGEARDOWNANN |
| Flap Selection | Degrees | GIA1_GEA1:DOIOP_C_EAU_FLAPS_POSITION.POSITION_DEG |
| Autopilot Engage-ment | On or Off | AUTOPILOT1:DOIOP_C_AFCS_1_ANNUNC.AP_ENGAGESTATE |
| Latitude | Radians | LatitudeExpression_Rad |
| Longitude | Radians | LongitudeExpression_Rad |
| Autopilot Vertical Mode | Ordinal | AutoPilot1:doIOP_C_AFCS_1_ANNUNC.PitchCoupledMode |
| Autopilot Horizontal Mode | Ordinal | AutoPilot1:doIOP_C_AFCS_1_ANNUNC.RollCoupledMode |

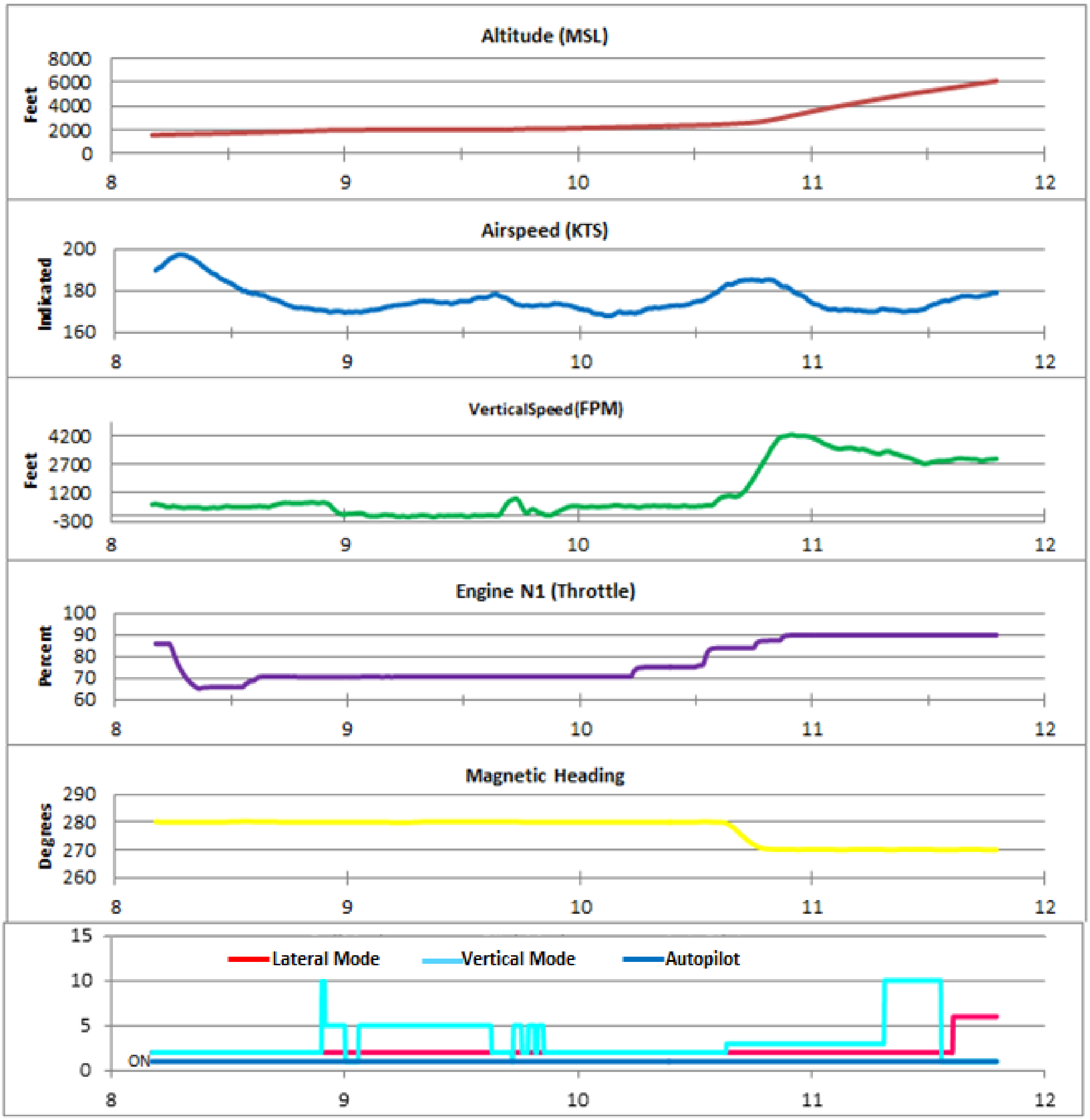
Table 3 shows an example of some of the flight parameters, units of measure, and variable names within the Frasca software package that were used for analysis.




| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | FRAME NU | TIME IN SE | LatitudeE | Longitude | AltitudeM | VertSpeed | ASI1:AIRS | PitchExpr | BankExpr | GIA1_429_ | AUTOPILO | AUTOPILO | AUTOPILOT1:DOIOP_C_AFCS_1 | | |
| 10 | 1 | 0.2 | 0.68645 | 1.333854 | 18.90394 | 0.0024 | 0.00128 | 2.332029 | -0.79707 | 0.226198 | 0 | 0 | 0 | | |
| 11 | 2 | 0.4 | 0.68645 | 1.333854 | 18.90396 | 0.004971 | 0.000587 | 2.331807 | -0.79707 | 0.225395 | 0 | 0 | 0 | | |
| 12 | 3 | 0.6 | 0.68645 | 1.333854 | 18.90396 | 0.00652 | 0.00026 | 2.33154 | -0.79707 | 0.224533 | 0 | 0 | 0 | | |
| 13 | 4 | 0.8 | 0.68645 | 1.333854 | 18.90396 | 0.002824 | 0.000115 | 2.33154 | -0.79707 | 0.223656 | 0 | 0 | 0 | | |
| 14 | 5 | 1 | 0.68645 | 1.333854 | 18.90396 | -0.01748 | 0.002226 | 2.33227 | -0.79731 | 0.222784 | 0 | 0 | 0 | | |
| 15 | 6 | 1.2 | 0.68645 | 1.333854 | 18.90396 | -0.00861 | 0.004185 | 2.332796 | -0.79754 | 0.221927 | 0 | 0 | 0 | | |
| 16 | 7 | 1.4 | 0.68645 | 1.333854 | 18.90396 | 0.003072 | 0.002455 | 2.332796 | -0.79773 | 0.221085 | 0 | 0 | 0 | | |
| 17 | 8 | 1.6 | 0.68645 | 1.333854 | 18.90396 | 0.006132 | 0.001088 | 2.332487 | -0.79798 | 0.220254 | 0 | 0 | 0 | | |
| 18 | 9 | 1.8 | 0.68645 | 1.333854 | 18.90396 | 0.002114 | 0.000482 | 2.332487 | -0.79826 | 0.219421 | 0 | 0 | 0 | | |
| 19 | 10 | 2 | 0.68645 | 1.333854 | 18.90396 | -0.01726 | 0.002358 | 2.33293 | -0.79843 | 0.218577 | 0 | 0 | 0 | | |
| 20 | 11 | 2.2 | 0.68645 | 1.333854 | 18.90396 | -0.02775 | 0.00499 | 2.333889 | -0.79843 | 0.217709 | 0 | 0 | 0 | | |
| 21 | 12 | 2.4 | 0.68645 | 1.333854 | 18.90396 | -0.03026 | 0.006545 | 2.334897 | -0.79831 | 0.216809 | 0 | 0 | 0 | | |
| 22 | 13 | 2.6 | 0.68645 | 1.333854 | 18.90396 | -0.02388 | 0.007085 | 2.335626 | -0.79831 | 0.215866 | 0 | 0 | 0 | | |
| 23 | 14 | 2.8 | 0.68645 | 1.333854 | 18.90396 | 0.0161 | 0.006677 | 2.336071 | 0.79831 | 0.214875 | 0 | 0 | 0 | | |
| 24 | 15 | 3 | 0.68645 | 1.333854 | 18.90396 | -0.01615 | 0.006238 | 2.336439 | -0.79842 | 0.213834 | 0 | 0 | 0 | | |
| 25 | 16 | 3.2 | 0.68645 | 1.333854 | 18.90396 | -0.0188 | 0.006164 | 2.336905 | -0.79853 | 0.212744 | 0 | 0 | 0 | | |
| 26 | 17 | 3.4 | 0.68645 | 1.333854 | 18.90396 | -0.02075 | 0.006272 | 2.337439 | -0.79853 | 0.211611 | 0 | 0 | 0 | | |
| 27 | 18 | 3.6 | 0.68645 | 1.333854 | 18.90396 | -0.01568 | 0.006179 | 2.337853 | -0.79871 | 0.210442 | 0 | 0 | 0 | | |
| 28 | 19 | 3.8 | 0.68645 | 1.333854 | 18.90396 | -0.00555 | 0.005352 | 2.337995 | -0.79888 | 0.209248 | 0 | 0 | 0 | | |
| 29 | 20 | 4 | 0.68645 | 1.333854 | 18.90396 | 0.002947 | 0.003417 | 2.337861 | -0.79915 | 0.208041 | 0 | 0 | 0 | | |
| 30 | 21 | 4.2 | 0.68645 | 1.333854 | 18.90396 | 0.007152 | 0.001515 | 2.337579 | -0.7995 | 0.206832 | 0 | 0 | 0 | | |
| 31 | 22 | 4.4 | 0.68645 | 1.333854 | 18.90396 | 0.006993 | 0.000671 | 2.3373 | -0.79987 | 0.205633 | 0 | 0 | 0 | | |
| 32 | 23 | 4.6 | 0.68645 | 1.333854 | 18.90396 | 0.006286 | 0.000298 | 2.337106 | -0.80022 | 0.204452 | 0 | 0 | 0 | | |
| 33 | 24 | 4.8 | 0.68645 | 1.333854 | 18.90396 | 0.01687 | 0.000132 | 2.336597 | -0.80055 | 0.203294 | 0 | 0 | 0 | | |
| 34 | 25 | 5 | 0.68645 | 1.333854 | 18.90396 | 0.047029 | 5.85E-05 | 2.335281 | -0.80092 | 0.202155 | 0 | 0 | 0 | | |
| 35 | 26 | 5.2 | 0.68645 | 1.333854 | 18.90396 | 0.030252 | 2.59E-05 | 2.334127 | -0.80142 | 0.201028 | 0 | 0 | 0 | | |
| 36 | 27 | 5.4 | 0.68645 | 1.333854 | 18.90396 | 0.006842 | 1.15E-05 | 2.333864 | -0.80186 | 0.199908 | 0 | 0 | 0 | | |
| 37 | 28 | 5.6 | 0.68645 | 1.333854 | 18.90396 | -0.01498 | 0.001221 | 2.334509 | -0.802 | 0.198785 | 0 | 0 | 0 | | |
| 38 | 29 | 5.8 | 0.68645 | 1.333854 | 18.90396 | -0.02496 | 0.00438 | 2.335435 | -0.802 | 0.197649 | 0 | 0 | 0 | | |
| 39 | 30 | 6 | 0.68645 | 1.333854 | 18.90396 | -0.01891 | 0.005752 | 2.336235 | -0.80187 | 0.196488 | 0 | 0 | 0 | | |
| 40 | 31 | 6.2 | 0.68645 | 1.333854 | 18.90396 | -0.02242 | 0.006308 | 2.336774 | -0.80187 | 0.195291 | 0 | 0 | 0 | | |
| 41 | 32 | 6.4 | 0.68645 | 1.333854 | 18.90396 | -0.01986 | 0.00636 | 2.337153 | -0.80213 | 0.194048 | 0 | 0 | 0 | | |
| 42 | 33 | 6.6 | 0.68645 | 1.333854 | 18.90396 | -0.03245 | 0.006677 | 2.337753 | -0.80223 | 0.19275 | 0 | 0 | 0 | | |
| 43 | 34 | 6.8 | 0.68645 | 1.333854 | 18.90396 | -0.03662 | 0.007818 | 2.338514 | -0.80223 | 0.191392 | 0 | 0 | 0 | | |
| 44 | 35 | 7 | 0.68645 | 1.333854 | 18.90396 | -0.03695 | 0.008501 | 2.339312 | -0.80223 | 0.18997 | 0 | 0 | 0 | | |
| 45 | 36 | 7.2 | 0.68645 | 1.333854 | 18.90396 | -0.0469 | 0.009159 | 2.340099 | -0.80235 | 0.188488 | 0 | 0 | 0 | | |
| 46 | 37 | 7.4 | 0.68645 | 1.333854 | 18.90396 | -0.05217 | 0.009534 | 2.340941 | -0.80249 | 0.18695 | 0 | 0 | 0 | | |
| 47 | 38 | 7.6 | 0.68645 | 1.333854 | 18.90396 | -0.05238 | 0.009704 | 2.341892 | -0.80269 | 0.185365 | 0 | 0 | 0 | | |
| 48 | 39 | 7.8 | 0.68645 | 1.333854 | 18.90396 | -0.03914 | 0.009803 | 2.342868 | -0.80295 | 0.183743 | 0 | 0 | 0 | | |
| 49 | 40 | 8 | 0.68645 | 1.333854 | 18.90396 | -0.0222 | 0.009377 | 2.343568 | -0.80331 | 0.182095 | 0 | 0 | 0 | | |
| 50 | 41 | 8.2 | 0.68645 | 1.333854 | 18.90396 | -0.01272 | 0.007956 | 2.343816 | -0.8038 | 0.180434 | 0 | 0 | 0 | | |
| 51 | 42 | 8.4 | 0.68645 | 1.333854 | 18.90396 | -0.00711 | 0.004698 | 2.343816 | -0.80444 | 0.178772 | 0 | 0 | 0 | | |
| 52 | 43 | 8.6 | 0.68645 | 1.333854 | 18.90396 | 0.007401 | 0.00231 | 2.343547 | -0.80515 | 0.177116 | 0 | 0 | 0 | | |
| 53 | 44 | 8.8 | 0.68645 | 1.333854 | 18.90242 | 0.098333 | 0.001024 | 2.343252 | -0.80582 | 0.175477 | 0 | 0 | 0 | | |
| 54 | 45 | 9 | 0.68645 | 1.333854 | 18.90242 | 0.112475 | 0.000454 | 2.341631 | -0.80648 | 0.173891 | 0 | 0 | 0 | | |
| 55 | 46 | 9.2 | 0.68645 | 1.333854 | 18.90242 | 0.110378 | 0.000201 | 2.337909 | -0.80729 | 0.172386 | 0 | 0 | 0 | | |

*Figure 10*. Excel Spreadsheet Produced for 11 Specific Flight Parameters.

Figure 10 shows a spreadsheet of some of the downloaded data for several flight parameters recorded by the simulator. More information about the extraction and transformation of the simulator data in preparation for analysis can be found in Williams et al. (2013).




| Vertical Modes | | | Lateral Modes | | |
|---|---|---|---|---|---|
| 0 | None | | 0 | None | |
| 1 | Pit | Pitch | 1 | Roll | Roll |
| 2 | VS | Vertical Speed | 2 | HDG | Heading |
| 3 | FLC_IAS | Flight Level Change – Indicated Air Speed | 3 | APR_GPS | Approach - GPS |
| 4 | FLC_Mach | Flight Level Change – Mach | 4 | APR_LOC | Approach – Localizer |
| 5 | ALT | Altitude hold | 5 | APR_VOR | Approach – VOR |
| 6 | VPTH | Vertical Path | 6 | NAV_GPS | NAV mode - using GPS |
| 7 | GS | Glide Slope | 7 | NAV_LOC | NAV mode - using localizer |
| 8 | GA | Go Around | 8 | NAV_LOC_BC | NAV mode - using localizer back course |
| 9 | ALTS | Selected Altitude Capture | 9 | NAV_VOR | NAV mode - using VOR |
| 10 | ALTV | Vertical Path Capture | 10 | GA | Go Around |

*Figure 11.* By AGL Stacked Graphs of Simulator Data.

**Graphs**

Using extracted simulator data, graphs of several continuous variables were created in Microsoft Excel. The following variables were graphed to assist us in our analyses: altitude, airspeed, vertical speed, engine power (N1), magnetic heading, autopilot use (on/off), and autoflight modes used. The x-axis of all graphs was expressed as time in minutes, and the y-axis was indicated by a scale appropriate to each variable. To compare the multiple variables simultaneously, graphs were stacked on top of each other, aligning time markers along the x-axis. Figure 11 illustrates these graphs for one of the high workload events analyzed for this report. More information about the construction and content of the graphs can be found in Williams et al. (2013).

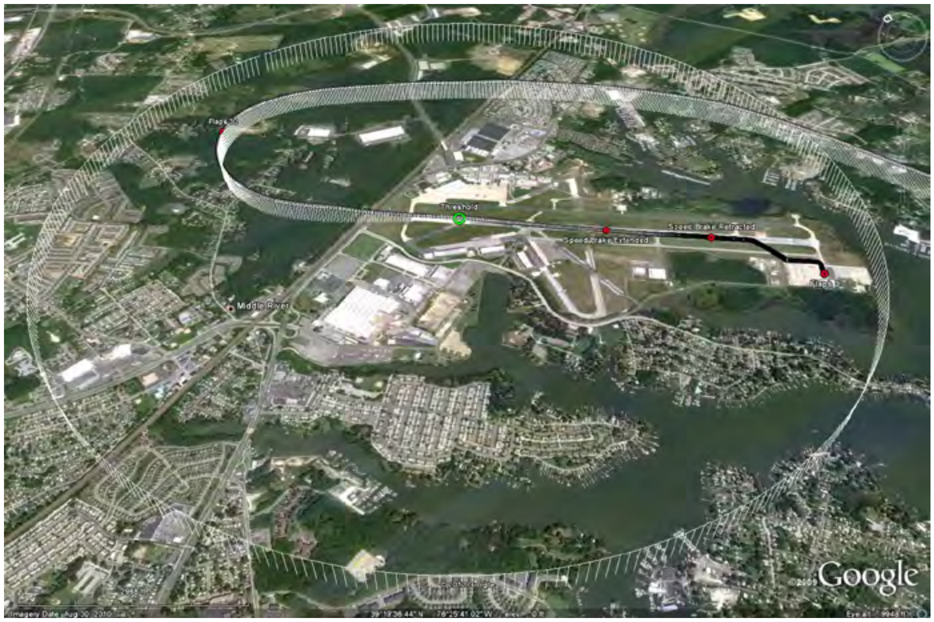



*Figure 12*. Example flight trajectory plotted in Google Earth.


*Figure 13*. Flight Path Trajectory With Additional Aircraft Data Selected.

**Google Earth Plots**

To assist in the analysis of the data, the flight path trajectories were plotted in Google Earth™. Figure 12 shows a sample flight trajectory for a circling approach and landing on runway 15 at KMTN, with a 1.3 nautical mile radius circle around the runway threshold as an obstacle clearance safe area, plotted in Google Earth.

The identification of specific events during the flight such as the use of the autopilot was indicated by uniquely formatted place marks so they could be easily distinguished within the flight path trajectory. Figure 13 shows a Google Earth plot of a flight trajectory with one of the place marks selected, showing the additional information available.

Developing Google Earth plots require the creation of standardized OpenGIS® KML files. Details of the KML file standard are available from the maintainers of the specification. Open Geospatial Consortium, Inc. at http://www.opengeospatial.org/standards/kml/. The procedure for creating KML files and place marks is described in detail in Williams et al. (2013).

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | Line | STRT_TIME | STOP_TIME | SPKR_ID | RCVR_ID | Transcription |
| 2 | 40 | 0:23:56 | 0:24:05 | ATC | Participant | CITATION SEVEN QUEBEC FOXTROT CLIMB AND MAINTAIN FLIGHT LEVEL TWO ZERO ZERO, LEAVING ONE SEVEN THOUSAND CONTACT WASHINGTON CENTER ON ONE THREE THREE POINT NINER. |
| 3 | 41 | 0:24:13 | 0:24:19 | Participant | ATC | CLIMB AND MAINTAIN FLIGHT LEVEL TWO ZERO ZERO LEAVING ONE SEVEN THOUSAND CONTACT WASHINGTON ON ONE THREE THREE DECIMAL NINER, FIVE SEVEN QUEBEC FOXTROT. |
| 4 | 42 | 0:26:32 | 0:26:37 | Participant | ATC | UH WASHINGTON CITATION FIVE SEVEN QUEBEC FOXTROT PASSING THROUGH ONE SEVEN THOUSAND FOR FLIGHT LEVEL TWO ZERO ZERO. |
| 5 | 43 | 0:26:40 | 0:26:46 | ATC | Participant | CITATION FIVE SEVEN QUEBEC FOXTROT WASHINGTON CENTER ROGER. PLEASE VERIFY THE REST OF YOUR ROUTING AND YOUR SQUAWK. |
| 6 | 44 | 0:26:48 | 0:27:26 | Participant | ATC | UH SQUAWK IS ONE SIX TWO THREE. AND UH MY ROUTING FROM UH MY ROUTING IS UH FROM NOTTINGHAM TO CASANOVA J48 TO MONTEBELLO, THEN DIRECT HOT SPRINGS, FIVE SEVEN QUEBEC FOXTROT |
| 7 | 45 | 0:27:27 | 0:27:28 | ATC | Participant | SEVEN QUEBEC FOXTROT ROGER. |
| 8 | 46 | 0:30:19 | 0:30:52 | ATIS | Participant | *INGALLS FIELD AIRPORT AUTOMATED WEATHER OBSERVATION ONE FOUR TWO TWO ZULU WEATHER. WIND TWO TWO ZERO AT FIVE, VISIBILITY SIX MILES, NINE HUNDRED OVERCAST. TEMPERATURE ELEVEN DEGREES CELSIUS, DEW POINT SEVEN DEGREES CELSIUS, ALTIMETER TWO NINER POINT EIGHT FOUR. INGALLS FIELD AIRPORT AUTOMATED WEATHER OBSERVATION ONE...* |
| 9 | 47 | 0:34:13 | 0:34:19 | ATC | Participant | CITATION SEVEN QUEBEC FOXTROT FOR TRAFFIC DESCEND AND MAINTAIN ONE SIX THOUSAND, CULPEPER ALTIMETER TWO NINER EIGHT SIX. |
| 10 | 48 | 0:34:21 | 0:34:26 | Participant | ATC | ONE SIX THOUSAND, SEVEN QUEBEC FOXTROT. |
| 11 | 49 | 0:38:59 | | Participant | Participant | Okay, one oh eight dess seven, and uh center one three four four, and uh uni one two three zero. Flaps |
| 12 | 50 | 0:40:09 | | Participant | Participant | And checklist complete. |
| 13 | 51 | 0:41:48 | | Participant | Participant | Okay, eleven degrees. Okay, landing weight - seven and a half - and two thousand four hundred and eighty - pounds. |
| 14 | 52 | 0:42:09 | 0:42:16 | ATC | Participant | CITATION FIVE SEVEN QUEBEC FOXTROT DESCEND PILOT'S DISCRETION, CROSS ONE FIVE NORTHEAST OF MONTEBELLO AT ONE ZERO THOUSAND, TEN THOUSAND. |

*Figure 14*. Sample Flight Communication Transcription.

## Flight Communication Transcription

The audio files of the flight communications were transcribed into Excel files with the use of Start Stop Universal™ software. This enabled the extraction of start and stop times for each transmission, including communications between ATC and the participant or other aircraft pilots included in the scenario. Since the participant's cockpit headset included a "hot" mic (on and recording continuously), the transcripts also included when a participant was recorded thinking aloud, and the simulator voice aural alerts heard in the cockpit. Each transcribed file started at zero hours, minutes, and seconds (00:00:00). Figure 14 illustrates what a transcription might look like; more information about the transcription process can be found in Williams et al. (2013).

## Voice Analysis

Previous research has found a relationship between different vocal qualities and stress or workload. For example, it has been found that speech fundamental frequency (pitch) and vocal intensity (loudness) increase significantly as workload increases and tasks become more complex (Brenner, Doherty, & Shipp, 1994; Griffin & Williams, 1987). Speech or articulation rate has also been shown to increase when the speaker is under stress associated with high workload (Ruiz, Legros, & Guell, 1990). Therefore, we decided to conduct various voice analyses as possible objective indicators of participant workload in this study.

To prepare each participant's audio files for the fundamental frequency ($F_O$) and articulation rate analyses, audio files containing the flight communications of each participant were exported into Sound Forge Audio Studio (Version 10). Sections of communication for each participant to be used in the analyses, described later, were identified and labeled; all audio of the ATC, experimenter, other pilots, and simulator noises were deleted from the file. Each identified section of communication was then cut and pasted into a single WAV file so that each participant had one audio file containing all audio sections to be analyzed.

For the $F_O$ analyses, these same audio sections were exported into WaveSurfer™ (Version 1.8.8p4), and $F_O$ was calculated at a rate of .01 s. The average articulation rate per section was then calculated using Praat™ software (Version 5.3.22; Boersma & Weenink, 2012; de Jong & Wempe, 2009). Articulation rates were then calculated by dividing the number of syllables by the total speaking time.


*Figure 15*. Four Camera Views of Cessna Mustang Simulator Cockpit. Starting From Top Left Rotating Clockwise – MFD, View Of Pilot, Pilot's PFD, Co-Pilot's PFD.

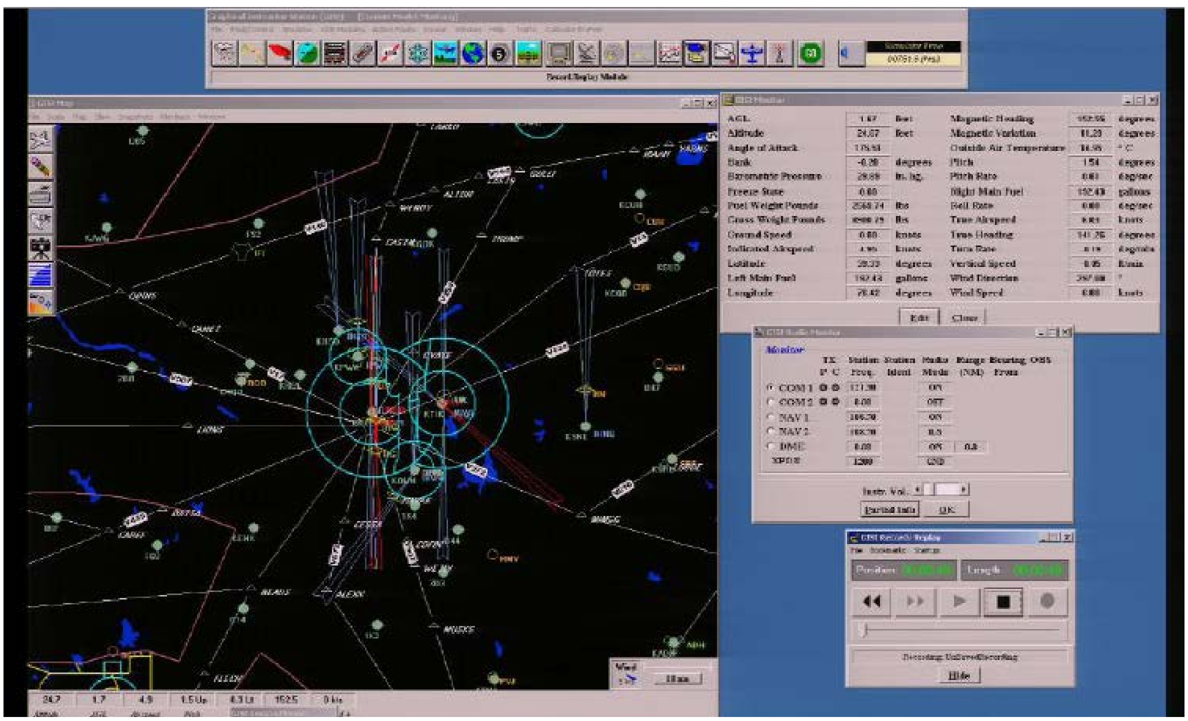


*Figure 16*. ATC Dynamic Navigation Map and Flight Parameter Display.

## Video Data

Two types of video data were collected, cockpit camera footage and a recording of a navigational map combined with limited flight parameter data. During data analysis, the recorded cockpit video feed from the four cameras could be viewed on one screen, as shown in Figure 15, or video from just one of the cameras could be selected to make it easier to see what was recorded. Although post-collection examination of the cockpit video data revealed a lower video quality than expected, they still served as valuable sources to confirm simulator flight parameter data by helping to place other data in context.

During data collection, video of a dynamic display of a navigation map, including a depiction of the participants' aircraft position, was used as a radar screen for ATC and was only available at the experimenter's station. A limited set of 40 flight parameters was displayed on the right hand side of the screen (see Figure 16), which allowed researchers and ATC to monitor participant performance in real-time. Video recordings of the navigation maps with the flight parameters were also used during data analysis.

## RESULTS

### Participant Demographics

Fourteen male pilots, type-rated to fly the Mustang as a single pilot, participated in the simulator portion of this study. During data collection, we discovered that one of the participants had no prior experience flying as a single pilot, so data from his flights were not included in any of the analyses reported below. In addition to a C510-S type rating, participants were either owner-operators of a Cessna Citation Mustang (*n*=7) or flew the Mustang as part of their jobs as corporate or contract pilots (*n*=6). Their ages ranged from 29 to 61 years, with a mean age of 48.9 years. In the year prior to the study, our participants reported flying the Cessna Mustang a mean of 153.7 hours (range: 68-350 hours) and flying the Mustang as a single pilot for a mean of 138.5 hours (range: 15-350 hours). General flying and Citation Mustang-specific flying history can be seen in Table 4. No significant differences in flight hours were found between study owner-operators and professional pilots.

Table 4. Participant Flying History.

| | Mean | Median | Range | SD |
|---|---|---|---|---|
| General Flying | | | | |
| Total number of flight hours | 3998.92 | 3950.00 | 1000 - 8130 | 2087.84 |
| Owner-operators | 3507.85 | 2500.00 | 1000 - 8130 | 2590.75 |
| Professional pilots | 4571.83 | 4425.00 | 2900 - 6381 | 1294.58 |
| Flight hours in the past year | 230.53 | 170.00 | 90 - 528 | 152.57 |
| Owner-operators | 201.14 | 170.00 | 90 - 528 | 151.09 |
| Professional pilots | 264.83 | 247.00 | 100 - 515 | 160.79 |
| Total number of jet hours as a single pilot | 331.61 | 210.00 | 100 - 1345 | 329.36 |
| Owner-operators | 287.86 | 230.00 | 100 - 475 | 136.98 |
| Professional pilots | 382.66 | 168.00 | 100 - 1345 | 481.69 |
| Flight hours in the past 3 months | 52.61 | 40.00 | 20 - 121 | 30.26 |
| Owner-operators | 51.43 | 40.00 | 25 - 100 | 28.09 |
| Professional pilots | 54.00 | 45.00 | 20 - 121 | 35.31 |
| Citation Mustang Specific | | | | |
| Flight hours with a mentor pilot | 11.16 | 5.00 | 0 - 35.00 | 12.62 |
| Owner-operators | 13.57 | 15.00 | 0 - 35.00 | 12.82 |
| Professional pilots | 8.36 | 0.00 | 0 - 25.20 | 12.96 |
| Flight hours in the past year | 153.69 | 125.00 | 68 - 350 | 89.61 |
| Owner-operators | 161.43 | 125.00 | 75 - 350 | 93.75 |
| Professional pilots | 144.66 | 119.00 | 68 - 325 | 92.45 |
| Flight hours in the past year as a single pilot | 138.46 | 100.00 | 15 - 350 | 99.78 |
| Owner-operators | 160.71 | 120.00 | 75 - 350 | 94.09 |
| Professional pilots | 112.50 | 83.50 | 15 - 325 | 108.49 |

Table 5. Personal Experience With Advanced Avionics and Automation.

| Questions Assessed | Mean | Median | SD |
|---|---|---|---|
| Overall Experience using different types of advanced avionics/ glass cockpits | 3.07 | 3.00 | 1.55 |
| Owner-operators | 3.28 | 4.00 | 1.38 |
| Professional pilots | 2.83 | 2.50 | 1.83 |
| Experience using the G1000 in the Citation Mustang or any other aircraft | 4.00 | 4.00 | 1.08 |
| Owner-operators | 4.14 | 4.00 | .90 |
| Professional pilots | 3.83 | 3.50 | 1.32 |
| Skill level using the G1000 in the Citation Mustang or any other aircraft | 4.08 | 4.00 | 0.95 |
| Owner-operators | 4.28 | 4.00 | 1.17 |
| Professional pilots | 3.83 | 4.00 | .75 |
| Experience using the G430/G50 or other similar Garmin IFR avionics systems | 3.77 | 4.00 | 1.42 |
| Owner-operators | 3.29 | 3.00 | 1.50 |
| Professional pilots | 4.33 | 5.00 | 1.21 |
| Experience using the other types of advanced avionics (e.g. Avidyne, Chelton, etc.) | 2.83 | 3.00 | 1.69 |
| Owner-operators | 2.57 | 3.00 | 1.51 |
| Professional pilots | 3.20 | 4.00 | 2.04 |
| Experience with using the FMS | 2.69 | 2.00 | 1.60 |
| Owner-operators | 2.71 | 3.00 | 1.79 |
| Professional pilots | 2.67 | 2.00 | 1.50 |
| Experience using stand-alone autopilot/auto flight systems | 3.85 | 4.00 | 1.40 |
| Owner-operators | 3.57 | 4.00 | 1.72 |
| Professional pilots | 4.16 | 4.50 | .98 |

1 = little experience/skill, 5 = very experienced/skilled

Pilots were asked to fill out a questionnaire assessing their experience with advanced avionics and automation. Analysis revealed that the pilots were fairly experienced in using the G1000, as well as other types of advanced avionics (e.g., Avidyne, Chelton). Some of the questions asked, along with rating means, standard deviations and ranges are presented in Table 5 (see Appendix B for the complete questionnaire). Ratings were given from 1 to 5, with a rating of 1 referring to having little experience and 5 being very experienced. No significant differences in self-reported experience or skill with advanced avionics and automation were found between the owner-operators and the professional pilots.

**Autopilot Use During the Experimental Flight**

Participants turned on the simulator's autopilot an average of 1 minute after take-off at a mean altitude of 901 ft MSL during leg 1 of the experimental flight (*SD* = 547 ft MSL). However, the participants fell within two distinct groups with regard to when they engaged the autopilot relative to their altitude on climb out. Nine of them turned it on at or below 854 ft MSL (*M* = 572 ft MSL, *SD* = 191 ft MSL, range: 305 to 854 ft MSL), and the other four engaged it at or above 1,408 ft MSL (*M* = 1,642 ft MSL, *SD* = 206 ft MSL, range: 1,408 to 1,886 ft MSL). The seven owner-operators engaged the autopilot at a mean altitude of 648 ft MSL (*SD* = 373 ft MSL), and the six professional pilots engaged it at a mean altitude of 1,195 ft MSL (*SD* = 599 ft MSL). Thus, in leg 1 most of the owner-operators were in the group of participants who initially engaged the autopilot earlier (at lower altitudes), and most of the professional pilots were among the group who initially engaged the autopilot later at higher altitudes. Additionally, the altitudes at which the owner-operators engaged the autopilot were more similar (i.e., smaller range of altitudes) than those altitudes at which professional pilots engaged the autopilot.

In leg 2 of the experimental flight, participants again turned on the simulator's autopilot an average of 1 minute after take-off but at a mean altitude of 1,148 ft MSL (*SD* = 584 ft MSL, range 335 – 2,014 ft MSL). Unlike the first leg, the altitudes chosen for engaging the autopilot were fairly evenly distributed throughout the range and owner-operators and professional pilots were, likewise, fairly evenly represented at all altitude levels in the range (low, medium, high) with regard to when the autopilot was engaged.

During leg 1, the participants had the autopilot engaged for an average of 94.4% of the time during their flights (*SD* = 2.7%) from take-off to landing, with the owner-operators using the autopilot slightly more (*M* = 95.4%, *SD* = 2.1%) than the professional pilots (*M* = 93.3%, *SD* = 3.0%). The flights, from take-off to landing, lasted an average of 50.2 minutes (*SD* = 3.81 minutes) with the average length of the flights flown by the owner-operators and the professional pilots being almost exactly the same.

During leg 2, the participants had the autopilot engaged for an average of 94.9% of the time during their flights (*SD* = 1.6%) from take-off to landing, again with the owner-operators using the autopilot slightly more (*M* = 95.7%, *SD* = 0.5%) than the professional pilots (*M* = 93.7%, *SD* = 1.9%). From take-off to landing, the leg 2 flights lasted an average of 57.11 minutes (*SD* = 4.93 minutes). When the two pilots who did not complete a missed approach procedure at KHSP are removed, the average length of the leg 2 flights rises to 58.92 minutes (*SD* = 2.82 minutes), with the professional pilots (*M* = 57.58 minutes, *SD* = 1.43 minutes) generally completing the leg only slightly faster than the owner-operators (*M* = 59.81 minutes, *SD* = 3.28 minutes).

**Analysis of Workload and Task Management of Four En Route Events**

Due to time and resource limitations, we focused our analyses on four events in the two experimental flights that were specifically scripted to involve high pilot workload. In the first leg from KTEB to KMTN, the two events subjected to detailed scrutiny were 1) the instruction from ATC to intercept the 208° Broadway (BWZ) radial following the completion of the departure procedure out of KTEB and 2) programming a reroute while at cruise and meeting a waypoint crossing restriction on the initial descent from cruise. In the second leg from KMTN to KHSP, we focused our analyses on 3) the completion of an expedited descent to accommodate another aircraft with an emergency, and 4) task completion and preparation for the approach into KHSP while facilitating communication from a lost pilot who was flying too low for ATC to hear.

Below are the findings of the analyses associated with these four events, individually, as well as a review of some overall findings across the two experimental legs. Due to the very small number of participants in our study, we were unable to generate sufficient statistical power. Therefore, our analyses were susceptible to type II errors, which are defined as accepting the null hypothesis when it is in fact false—meaning that significant differences between groups may not have been detected. Additionally, due to the small number of participants, the statistically significant differences found among our participants, reported below, illustrate true differences among the study participants (i.e., our sample). However, caution should be exercised when generalizing our findings to other pilots who were not participants in this study (i.e., the population of single pilots flying VLJs/ELJs as a whole). In describing our findings, for the most part, we only report differences observed in the performance of owner-operators and professional pilots if the differences were statistically significant or, in the case of frequency data, appeared to be relatively large.

**Event 1: Interception of the Broadway (BWZ) Radial**

Upon completing the TEB6 departure off runway 24 at KTEB, the aircraft should have been on a heading of 280° and level at 2000 ft MSL. In our scenario, the participants were then told to continue to fly at 2000 ft MSL to accommodate crossing traffic descending into LaGuardia International Airport. At 15 nm DME from TEB, ATC told them to "fly heading 270° to intercept the Broadway, Bravo, Whiskey, Zulu, 208° radial to BIGGY, then as filed." After reading the clearance back correctly, the participants were also given the instructions to "Climb and maintain 6000, contact New York Departure on 132.80."

Thus, in addition to looking for the crossing traffic headed to LaGuardia, there were four main tasks that had to be accomplished: a heading change, intercepting a radial off a VOR, a climb to a new altitude, and a change in radio frequency and requirement to check in with a new controller. The participants had to remember each of these tasks with their associated numbers (heading, radial, altitude, frequency) and consider how to accomplish them and in what order. Three of the tasks (change in heading, altitude, and frequency) are commonly performed during IFR flight, and each can be accomplished fairly quickly by proficient pilots. Therefore, we thought it likely that the subtasks required for each would be completed in their entirety before moving on to those associated with a new task, rather than interleaving them across the three tasks. For example, we expected that a pilot would verify the radio in use and then switch to another task, such as dialing in a new heading, before going back to the original task and dialing in the new radio frequency. However, one exception to our expectation that these three tasks would be performed sequentially, rather than interleaved, was that we thought some pilots, after having changed to the new radio frequency, might choose to complete other tasks, such as dialing in the new altitude and initiating the climb to 6000 ft, prior to checking in with the new departure controller.

The fourth task in this clearance, intercepting the BWZ radial, is quite different from the other three tasks with regard to its cognitive and temporal demands. There are a number of ways to accomplish a radial intercept using the G1000, although none of them is as simple as pressing a button or two or locating the option in a dropdown menu. As a consequence, the participants had to consider how to use the automation, if at all, to complete an unexpected task, which is relatively uncommon.

The three most likely strategies pilots were expected to employ to accomplish this task using the G1000 are presented in Table 6.

In the first strategy, OBS function in the G1000 is used in conjunction with the selection of the BIGGY waypoint and the desired arrival course. In the second strategy, the pilot alters the flight plan by entering the BWZ VOR prior to BIGGY, thereby creating a flight plan leg to intercept. The third strategy duplicates traditional navigation to VOR radials using the CDI and the HSI display on the PFD. The first two require an understanding of unique G1000 functioning (the first: OBS function with NAV mode, and the second: altering a flight plan) whereas the third strategy requires knowledge of how to set up the G1000 to navigate using ground-based navaids. The steps for the third strategy are not that different from those for VOR navigation in aircraft without glass cockpits and advanced avionics.

***Unscripted flight director failure***. Flight simulators are notoriously challenging to work with in research settings. Inaugural studies, such as ours, tend to reveal completely unexpected behaviors. Despite pre-study preparations, including multiple shakedown runs, a malfunction manifested itself within the first week of data collection in the form of a flight director (FD) failure. As the aircraft approached maximum operating velocity ($V_{mo}$) or "redline" on the airspeed indicator, the FD began to bounce up and down in an unpredictable fashion. Subsequent observation of the video showed that the degree of amplitude appeared to be within ± 10 degrees of the horizon. The MAXSPD flag above the airspeed indicator tape also flashed intermittently. This problem was evident from time to time throughout the experimental flights, typically recurring whenever the pilot used the autopilot (AP) in vertical speed (VS) mode. However, it was only a significant issue affecting participant performance during the departure and initial climb out from KTEB.

Several pilots who experienced this behavior actually stated out loud that they had an AP failure or a problem with their FD. The majority of pilots who experienced this malfunction immediately came "out of role" and asked the researchers if the failure was intentional; they were told that it was not. Unfortunately, this malfunction added a significant amount of distraction to the challenges of flying an already difficult departure procedure. Many pilots chose to focus on trying to solve this problem either by themselves, while staying in role as a pilot subject, or out of role in conversation with researchers seated at the experimenter station.

Despite attempts to resolve the FD problem, such as AP disengagement/reengagement and mode changes, none were successful and, in hindsight, actually only served to further confuse the issue. Halfway through data collection, we postulated that the tailwind experienced on climb out might somehow be confusing the program logic to thinking that the aircraft was beyond $V_{mo}$ when it was in fact still below. We removed the wind programming from the takeoff and climb out segment, noted a cessation of the erroneous FD/AP behavior, and believed we had solved

Table 6. Expected Strategies for Programming the BWZ Radial Intercept.

| | |
|---|---|
| Using the GPS OBS Function | While in heading mode, bring up the flight plan<br>Select (highlight) BIGGY on the flight plan<br>Press the Direct button and press Enter<br>Select OBS function using the OBS soft key on the PFD<br>Turn the CRS knob to select 208°<br>After the G1000 displays the course, select NAV mode on the autopilot |
| Altering the Flight Plan | While in heading mode, bring up the flight plan<br>Select (highlight) BIGGY on the flight plan<br>Enter BWZ, which inserts BWZ prior to BIGGY on the flight plan<br>Select (highlight) BIGGY on the flight plan<br>Press the Menu button<br>Select Activate Leg and press Enter<br>Select NAV mode on the autopilot |
| Using VOR Navigation | While in heading mode, dial in the frequency for the BWZ VOR (114.2) in a nav radio (1 or 2) and make it the active nav frequency<br>Press the CDI button on the PFD to switch to the appropriate VOR (1 or 2) to match the nav radio with the BWZ VOR frequency (1 or 2)<br>Set the OBS to 208° on the CDI<br>Select NAV mode on the autopilot |

the issue. However, only after the study was completed did we discover that the FD was responding correctly to an incorrect "gain" related to an unintentional turbulence setting. This increased gain manifested itself by producing a very high vertical turbulence component. As such, the FD was trying to manage this exaggerated component while maintaining congruence with the modes and values selected on the autopilot control panel.

Because of the significant challenge produced by this apparent malfunction, many pilots were unable to control the aircraft and still adhere to the requirements of the departure out of KTEB or sustain a level of flight precision as described in the practical test standards for ATP. However, in all cases the pilots remained focused on the number one priority of flying the aircraft and several advised ATC of their situation and requested help in the form of vectors or a change in altitude.

Of the eight participants who experienced the unscripted FD failure, four (three owner-operators and one professional pilot) encountered quite a bit of difficulty in managing the failure; the other four (two owner-operators and two professional pilots) managed the failure fairly well, although all eight committed errors of various types during the event (discussed later). All four pilots who had significant difficulty with the failure, one who managed the FD failure fairly well, and one who did not experience the failure at all ($n$ = 6) were unable to successfully accomplish the major task during this first event (i.e., set up to intercept the BWZ 208° radial). All of the other participants, three with the FD failure and four without it, successfully accomplished the Event 1 task ($n$ = 7). Detailed descriptions of participant performance and completion of tasks in Event 1 follow.

***Overall flight performance during Event 1***. The initiation of this event began when the pilots leveled out at 2,000 ft MSL at the completion of the TEB6 departure procedure and ended when the aircraft was 30 nm from the TEB VOR and the participants were given the clearance from ATC to fly direct to BIGGY. The amount of time the event lasted was associated with the speed with which the participant was flying and ranged from 03:01 to 06:02 ($M$ = 04:51, $SD$ = 01:08). Those who successfully accomplished the task took an average of almost five minutes to do so ($M$ = 04:59, $SD$ = 0:22, range = 04:42 to 05:39).

Although the workload during this event was high, and even more so for those experiencing the unscripted FD failure, most flew the aircraft within the parameters expected of experienced pilots. All participants maintained engine interstage turbine temperature (ITT) below the limit of 830°, responded to all radio calls from ATC, achieved the heading turn to 270°, and climbed to 6,000 ft MSL. No one forgot to raise the gear or retract the flaps, no excessive yaw was observed, and only one pilot had pitch inputs that exceeded 16° nose up (25.91° nose up). Those whose performance on a particular parameter exceeded what might be expected were typically those dealing with the FD failure. For example, pilots began the event on a heading of 280° and were instructed to turn left to a heading of 270° by ATC during the event; four of the five pilots who exceeded 30 degrees of bank were dealing with the FD failure and did so while actually correcting to the right. Similarly, two of the three pilots whose vertical speed during the event exceeded 3,500 fpm. (5,399 and 8,766 fpm) had the unscripted failure.

It was obvious that the unscripted FD failure was a distraction that was likely associated with the (sometimes significantly) diminished performance of a few pilots; however, while addressing the problem, none of them flew the aircraft in a way which put them in danger with regard to loss of control. Nonetheless, heading and altitude excursions were common and several errors or difficulties were observed such as reporting their heading to ATC incorrectly, readback errors, dialing in the wrong communication frequency, neglecting to check in with a new controller, forgetting to select/enter a vertical or lateral mode, and keeping the autopilot engaged and/or leaving the FD on while hand flying during response to the FD failure (see Table 7 for a list of all errors observed during Event 1).

Additionally, the ability to accomplish the overall task (set up the aircraft to intercept the BWZ 208° radial to BIGGY) was seriously compromised for a few participants with the FD failure due to task saturation ($n$ = 5). Even so, four of those participants appropriately attempted to reduce the workload associated with this task by requesting vectors from ATC. Most participants with the FD failure maintained their overall composure and professionalism, including during radio calls to ATC, and at no point during their difficulties did any participant give up or stop trying to fly the simulator.

Eleven participants used only the Com 1 radio, one participant used only the Com 2 radio, and one participant alternated between Com 1 and Com 2 radio for all communications with ATC during this event. One participant who used only the Com 1 radio had the emergency frequency (121.5) dialed into the Com 2 radio but was not monitoring the frequency. During the event, participants were instructed to change frequency and check in with a new departure controller. Many participants dialed in the new frequency as it was being given but took between 10 s and 2 min.10 s from the end of the clearance until actually contacting the new controller ($M$ = 00:52, $SD$ = 00:40 , median = 00:36).

Eleven participants also entered in the new heading of 270° while ATC was giving the clearance so that their aircraft had already initiated the turn before communication with ATC was completed. The other two participants, both professional pilots, initiated the turn to the new heading 3 s and 10 s after the end of the radio call with ATC. The amount of time from the end of ATC's request that the aircraft climb to 6000 until the climb was initiated ranged from 4 to 51 s ($M$ = 00:22, $SD$ = 00:15, median = 00:21); The professional pilot who took 51 s to initiate his climb had not set up the automation correctly and did not catch his error until contacted by ATC about his failure to climb as directed.

Observable errors committed during the event are shown in Table 7. All pilots made at least one error during the event, although one professional pilot made only one error (exceeded 200 KIAS under the Class B veil for 10 s). All other participants made two or more errors during the event. An owner-operator who was dealing with the FD failure committed the greatest number of errors, including various airspeed violations ($n$ = 9).

A factorial MANOVA was conducted and no significant differences in the number of errors committed during Event 1 were found between owner-operators and professional pilots, $F(1,10) = 2.27, p = .16$, or between those who did and did not experience the FD failure, $F(1,10) = 1.37, p = .27$. Although no significant interaction effect between pilot type and experience with the FD was found, Wilk's $\lambda = .84, F(2,8) = 0.78, p = .49$, it should be noted that a greater number of owner-operators ($n$ = 5) were confronted with the FD failure than were professional pilots ($n$ = 3).

Table 7. Errors[1] Committed During High Workload Event 1.

| | All Participants( n=13) | Owner-Operators (n=7) | Professional Pilots (n=6) | Unscripted FD Failure (n=8) | No FD Failure (n=5) |
|---|---|---|---|---|---|
| Exceeded $V_{mo}$ | 3 | 2 | 1 | 2 | 1 |
| >200 KIAS below Class B veil | 7 | 3 | 4 | 3 | 4 |
| >250 KIAS in Class B | 2 | 2 | 0 | 2 | 0 |
| >200 KIAS in Class D | 7 | 4 | 3 | 3 | 4 |
| Leveled off at incorrect altitude | 2 | 1 | 1 | 1 | 1 |
| Incorrect heading (<3°) | 6 | 3 | 3 | 2 | 4 |
| Incorrect heading (>10°) | 6 | 4 | 2 | 5 | 1 |
| Forgot to check in with Departure ATC | 2 | 1 | 1 | 1 | 1 |
| Comm/readback errors[2] | 17 | 7 | 10 | 11 | 6 |
| Wrong ATC frequency | 1 | 1 | 0 | 1 | 0 |
| Wrong Nav radio selected | 1 | 1 | 0 | 1 | 0 |
| Lack of sufficient thrust for climb | 2 | 2 | 0 | 2 | 0 |
| Forgot to climb | 1 | 0 | 1 | 1 | 0 |
| Vertical mode errors | 2 | 1 | 1 | 1 | 1 |
| Lateral mode errors | 4 | 3 | 1 | 3 | 1 |
| Does not/delays disconnect AP with FD failure | 2 | 2 | 0 | 2 | 0 |
| Reverse sensing when setting up OBS | 1 | 1 | 0 | 1 | 0 |
| Total errors | 66 | 38 | 28 | 42 | 24 |
| Average error rate per participant | 5.08 | 5.43 | 4.67 | 5.25 | 4.80 |

[1] "Errors" includes only those that were observable and does not include some difficulties with flight path management described elsewhere in this report.
[2] Number of communication (e.g., reports on wrong heading) or readback errors over a total of 10 pilots

Table 7 reveals that airspeed violations in different types of airspace and small heading errors (less than 3°) were fairly prevalent, even among those participants who did not experience the FD failure. Most of the other errors associated with flight path management (i.e., lack of sufficient thrust to climb, vertical and lateral mode errors) as well as most readback or communication errors with ATC were not present in flights without the unscripted failure.

***Automation use, flight path management, and the BWZ radial intercept***. All G1000 inputs were made without hesitation and only one input error, which was quickly corrected, was observed during the event. All pilots had turned their autopilots on prior to the start of this event, but two pilots who were dealing with the unscripted FD failure had the autopilot turned off when the event began and two others, also dealing with the failure, had it on but turned it off not long after the event began. Five

participants, four of whom experienced the FD failure, had the FD engaged when the AP was not also engaged at some point during this event. Three of these pilots, including the one who did not have the FD failure, had the FD displayed but it was not programmed. Consequently, the FD was prompting flight control inputs that differed substantially from those actually being made. This FD behavior could be distracting and potentially dangerous. One participant with the FD failure attempted to get the displayed, but unprogrammed, FD to match his control inputs by changing his VS climb rate.

One pilot left the AP engaged and another was slow to disengage it when the FD failure problems were encountered. Although no Cessna Citation Mustang emergency or abnormal checklist for a FD failure existed when this study was conducted, disengaging the AP when the FD has failed is necessary so that the AP does not follow erroneous FD data. All pilots who turned off the AP while responding to the unscripted failure, turned it back on within a few minutes of experiencing the failure and were able to use the AP and FD fairly uneventfully for the remainder of their flights even though the FD failure momentarily reappeared on occasion.

At the initiation of this event (level off at 2,000 ft MSL), 12 pilots had heading mode engaged and one was using NAV mode. The sequence of lateral and vertical modes used by pilots during this event can be seen in Tables 8 and 9.

The rate of climb selected by those participants who used VS mode for all or part of the climb from 2,000 to 6,000 ft MSL ranged from 300 fpm to 2,700 fpm; four participants set the rate of climb at just one value during the event (300 fpm, 1,000 fpm, 2,000 fpm, and 3,000 fpm), whereas seven participants set the initial rate of climb and then adjusted it higher once ($n$ = 6) or even twice ($n$ = 1) when dissatisfied with the climb performance. One participant selected 300 fpm and only increased to 400 fpm but the other six initially selected a much higher rate of climb (range = 1,200 to 3,000 fpm, $M$ = 1,700 fpm, $SD$ = 699 fpm) and increased the rate of climb an average of 700 fpm ($SD$ = 255 fpm, range = 2,000 to 2,700 fpm).

Table 8. Sequences of Lateral AP Modes Used by Participants During Event.

| Lateral Mode Sequences[1] | All Participants (n=13) | Owner-Operators (n=7) | Professional Pilots (n=6) | Had Unscripted FD Failure (n=8) | Successfully set up BWZ radial intercept |
|---|---|---|---|---|---|
| HDG | 4 | 3 | 1 | 3 | no |
| HDG-NAV(GPS) | 3 | 1 | 2 | 2 | yes |
| HDG-NAV(GPS)-ROL | 1 | 1 | 0 | 1 | no |
| NAV(GPS)-HDG-ROL-HDG | 1 | 1 | 0 | 1 | no |
| HDG-NAV(VOR) | 3 | 1 | 2 | 1 | yes |
| ROL-HDG-NAV(GPS) | 1 | 0 | 1 | 0 | yes |

[1] HDG=Heading mode, NAV=Navigation mode, ROL=Roll mode, GPS=navigation signal provided by global positioning satellites, VOR=navigation signal provided by very high omnidirectional radio range

Table 9. Sequences of Vertical AP Modes Used by Participants During Event 1 Climb

| Vertical Mode Sequences[1] | All Participants (n=13) | Owner-Operators (n=7) | Professional Pilots (n=6) | Had Unscripted FD Failure (n=8) |
|---|---|---|---|---|
| VS | 7 | 3 | 4 | 6 |
| FLC | 3 | 2 | 1 | 0 |
| VS-FLC | 2 | 1 | 1 | 1 |
| VS-PIT | 1 | 1 | 0 | 1 |

[1] VS=Vertical Speed mode, FLC=Flight Level Change, PIT=Pitch mode

When FLC was used to accomplish all or part of the climb from 2,000 to 6,000 ft MSL, the five participants utilizing this mode selected airspeeds ranging from 171 KIAS to 219 KIAS ($M$ = 195 KIAS, $SD$ = 22 KIAS).

Findings in Table 7, presented earlier, suggest that several of the automation errors committed during this event may have been at least partly associated with the very high workload experienced by pilots during the unscripted FD failure. These errors included such things as forgetting to engage the NAV mode after setting up the avionics for the BWZ radial intercept, selecting VS for the climb but neglecting to set the number of feet per minute at which to climb, or forgetting to select a vertical or lateral mode entirely. Four participants (two with and two without the FD failure) demonstrated very poor flight path control while in manual flight such as inability to maintain straight and level flight—multiple descents, climbs, and lateral deviations were common.

As described above, we expected that one of three strategies would be used by pilots to accomplish the task of setting up the aircraft to intercept the BWZ 208° radial. Table 10 indicates the strategies actually employed.

Seven participants completed the task successfully. However, two first made errors they later corrected. The first was a professional pilot who originally tried to go direct to BWZ but realized it was an error after the aircraft turned toward BWZ; he then successfully accomplished the task by using the GPS OBS function. The second was an owner-operator who set up the automation to intercept a course line between BIGGY and a waypoint that followed in the flight plan (COPES). ATC cleared him back to a heading of 270° and the pilot realized his mistake and altered his flight plan by inserting BWZ prior to BIGGY. The shortest amount of time required for programming was 51 s for a professional pilot who altered his flight plan. The longest amount of time needed for programming was 05:11 by an owner-operator who also altered his flight plan but interleaved a number of other tasks (e.g., dialing in 6000 ft climb) while doing so. The median time required for successfully completing this task was 01:07 (excluding the participant who took the longest: $M$ = 01:10, $SD$ = 00:40).

As stated earlier, six participants were unsuccessful in completing the task. Five of them had the unscripted FD failure (though three who *were* successful also had FD failure problems). Two of the six unsuccessful participants attempted to use VOR navigation; one forgot to complete the final step of selecting NAV on the AP panel and the other was not able to finish configuring the avionics because of the high workload associated with the FD failure. Another participant programmed direct to BIGGY rather than setting up for the BWZ radial intercept. When ATC queried about the aircraft's heading the pilot was unable to respond and correct due to high workload. The other three unsuccessful participants appeared cognitively saturated with the failure and either never attempted or did not have a chance to attempt to complete the task; all three did request vectors direct to BIGGY though, as did one other who was unsuccessful in completing the task and was dealing with the FD failure.

To summarize, over half of the participants ($n$ = 8) were initially unsure as to how to accomplish the clearance to intercept a VOR radial using the G1000. After first making an error, two corrected and adopted a successful strategy; one attempted a correct strategy but did not engage the correct AP mode so was ultimately unsuccessful. Five participants were task saturated in dealing with the unscripted FD failure and were also unsuccessful in completing the task although four did ask for vectors in an attempt to comply with the clearance.

***Aircraft and FAR limitations***. While addressing the unscripted flight director failure, three pilots exceeded the aircraft maximum operating speed ($V_{mo}$), one of them on two separate occasions 90 s apart. Three of these excursions were momentary lasting 6 s or less but the fourth lasted 24 s. Surprisingly, all participants except for one, an owner-operator who experienced the FD failure, also violated various airspeed limitations relative to airspace or altitude during this event: two exceeded 250 KIAS while in class B airspace and below 10,000 ft MSL, seven exceeded 200 KIAS while flying under the class B veil, and seven exceeded the 200 KIAS speed restriction while flying through Morristown New Jersey's class D airspace on their way to intercepting the BWZ radial to BIGGY. Four participants violated two different types of airspace speed restrictions. Three of the airspace speed violations only lasted between 10 and 20 s. Table 7, presented earlier, summarizes the various types of speed violations committed by participants during Event 1.

***Checklist and chart usage***. Only one participant could be observed using a paper checklist (most likely the climb checklist) during this event, and he appeared to either complete or suspend

Table 10. Strategies for Setting up the BWZ 208° Radial Intercept.

| | All Participants (n=13) | Owner-Operators (n=7) | Professional Pilots (n=6) | Experienced FD Failure (n=8) |
|---|---|---|---|---|
| Used the GPS OBS function | 1 | 0 | 1 | 0 |
| Altered the flight plan | 3 | 1 | 2 | 2 |
| Used VOR navigation | 3 | 1 | 2 | 1 |
| Never attempted or did not complete task | 6 | 5 | 1 | 5 |

it when workload increased. It is possible that some participants completed this checklist either before or after the event, may have completed it during the event but silently from memory (so it was not obvious that it was being performed) or forgot to complete it. Given the high degree of workload during this event, postponing the climb checklist, if they in fact they did postpone it, was probably a good decision in terms of prioritizing tasks. This was particularly true for those participants who also had the unscripted flight director failure.

During this event, four participants referred to paper en route charts, at least two referred to charts on Apple iPads™ they had brought with them, and four appeared to only be referring to the MFD with regard to confirming their position and/or the location of the BWZ VOR and its NAV frequency.

***Pilot demeanor and general workload management***. A majority of the pilots displayed very professional behavior and appeared relaxed, confident, and calm during the event—even the eight who experienced the unscripted FD failure. Nonetheless, it was clear that instrument scan tended to break down for those experiencing the FD failure, and one owner-operator in particular focused intently on something on the PFD and experienced significant altitude and heading excursions in manual flight while doing so. A few others with the FD failure also displayed some signs of stress such as rocking back and forth in the seat and pressing on the right rudder pedal, causing a significant slip, as indicated by the slip/skid indicator.

An owner-operator wrote down the clearance to intercept the BWZ 208° radial when ATC first gave it—the only participant to do so; seven participants asked for the clearance to be repeated and five of them wrote it down during that repetition. The two participants who did not write down the repeated clearance appeared task-saturated with the FD failure and were two of the four participants who requested radar vectors instead. Only one of the participants who experienced a FD failure and was not successful in setting up the BWZ 208° radial intercept did not request radar vectors.

All of the participants during this event employed a workload management strategy characterized by quickly completing common tasks that involved few steps and taking care of those that required more thought and/or effort later. For example, 11 of the 13 pilots dialed the new heading of 270° as the controller gave the clearance to turn so that the aircraft, which were all in heading mode, had already begun the turn to the new heading by the end of the radio call. Similarly, several pilots entered 6,000 ft in the altitude reference window as ATC was issuing the clearance to climb. However, there was a longer delay in pilots actually initiating the climb ($M$ = 00:22, $SD$ = 00:15) as a vertical mode had to also be selected, which some did after accomplishing other tasks (or forgot to do, in the case of two participants). Interestingly, a few pilots read components of ATC clearances back not in the order that they were given by ATC, but in the order in which they intended to, or had already started to, complete the tasks. For example, when ATC said "Climb and maintain 6000, Contact New York Departure on 132.80" several participants read back the new frequency first, as they were dialing it into the standby radio, and then the clearance to climb to 6000 ft.

The most time-consuming discrete task during Event 1 was setting up the aircraft to intercept the BWZ 208° radial.[1] All pilots who used or attempted to use one of the three strategies identified earlier to accomplish this task outlined earlier did so by interleaving other tasks or subtasks. Some of these other subtasks pertained to initiating the climb or adjusting the rate of climb, making the radio call to check in with the new departure controller, dealing with aircraft anomalies associated with the FD failure, and scanning the cockpit instruments, among others. When interleaving subtasks in this way, pilots must recall what steps they have and have not yet accomplished for the various tasks under completion. Distractions, poor concentration, and poor memory can impair the ability to keep track of task status. Apparent problems with cognitive processing were seen in a few of the cases where pilots completed several of the subtasks associated with a task but forgot to complete all of them, such as pressing NAV as the final step in setting up the autoflight system or by selecting VS mode but not entering in a rate of climb. One participant, in particular, chose somewhat unusual places to segment tasks into subtasks and this may have contributed to errors he made in completing some of them. For example, he started to dial in a new altitude to climb to but stopped before it was fully entered and then switched to typing in the first letter of the BWZ VOR in his flight plan but then switched to a third task before the entire VOR name had been entered.

Workload strategies employed by some of those who were faced with the unscripted FD failure included interleaving of tasks but also included attempting to lessen the amount of work associated with accomplishing a task, such as asking ATC for vectors instead of trying to program the G1000 for the BWZ radial intercept. A few of these participants also clearly shed tasks, such as simply acknowledging ATC's call of crossing traffic rather than also looking for it on cockpit traffic displays. Those who were most task-saturated with the FD failure focused appropriately on maintaining aircraft control and shed varying amounts of other tasks associated with ATC clearances. However, in some cases it was more likely a case of forgetting to accomplish some step (e.g., neglecting to press the flip-flop button to move the new ATC frequency from standby to active) rather than consciously choosing not to perform it. As described earlier, most of those experiencing the FD failure mentioned experiencing a problem over the radio, but some of those comments were directed to the researchers rather than to ATC. None of the participants declared an emergency or requested a hold or some other delaying tactic from ATC to give them time to sort out the problems they were experiencing.

During the post-flight debriefing interviews, several participants said they subscribed to the "aviate-navigate-communicate" prioritization of tasks in the cockpit and that they tried to complete short and easy tasks first to get them out of the way. A few also said that they tried to accomplish as many tasks as they could early in a flight to reduce the number of tasks to be completed later.

[1]A discrete task is one which involves one or more steps which, once accomplished, mark the end of that task. In contrast, continuous tasks are those whose steps must be repeated over and over again throughout a particular phase or flight. Changing a radio frequency is a discrete task; monitoring cockpit instruments is a continuous task.

Table 11. Pilot Flying History in Hours by Major Task,[1] Success Status, and Experience of FD Failure.

| | | Successful (n=7) | | Unsuccessful (n=6) | | FD Failure (n=8) | | No FD Failure (n=5) | |
|---|---|---|---|---|---|---|---|---|---|
| | | M | SD | M | SD | M | SD | M | SD |
| General Flying | Total | 4637.29[a] | 2010.21 | 3254.17[a] | 2090.03 | 4554.50 | 2338.71 | 3110.00 | 1378.59 |
| | Past year | 302.43[b] | 177.31 | 146.67[b] | 49.67 | 272.88 | 170.76 | 162.80 | 97.40 |
| | Past 3 months | 62.00[c] | 34.93 | 41.67[c] | 21.60 | 62.00 | 34.88 | 37.60 | 12.70 |
| | Single pilot jet | 385.14 | 439.77 | 269.17 | 139.94 | 296.38 | 133.53 | 388.00 | 536.45 |
| Citation Specific | Past year | 170.43 | 117.69 | 134.17 | 42.48 | 185.88 | 100.04 | 102.20 | 34.53 |
| | Single pilot past year | 142.86 | 135.43 | 133.33 | 42.74 | 185.25 | 100.49 | 63.60 | 28.50 |

[1] The major task to be completed in this high workload event was setting up the aircraft for intercepting the BWZ 208° radial.
[a] p = .05
[b] p = .002
[c] p = .03

***Pilot background and experience***. Table 11 presents the piloting experience of participants who were and were not successful in setting up the G1000 to intercept the BWZ radial and for participants who did and did not experience the unscripted FD failure.

A MANOVA was conducted and main effects were found for the total number of flight hours accrued, $F(1,10) = 4.91$, $p = .05$ , partial $\eta^2 = .33$, the number of hours flown in the past year, $F(1,10) = 18.32$, $p = .002$ , partial $\eta^2 = .65$, and the number of hours flown in the previous three months, $F(1,10) = 6.36$, $p = .03$, partial $\eta^2 = .39$, on success with the Event 1 task. Not surprisingly, pilots who had successfully completed the Event 1 task had flown a significantly greater number of hours overall, in the past year, and in the previous three months, than those who were unsuccessful. This effect was found for hours flown in all types of aircraft, not just those flown in a Cessna Citation Mustang or as a jet single-pilot. Despite how disruptive the unscripted FD failure appeared to be for many participants, the MANOVA revealed no interaction effects between having had the failure (or not) with whether or not the pilot was successful in accomplishing the task, Wilk's $\lambda = .69$, $F(4,6) = 0.69$, $p = .63$.

Table 12. ISA and NASA RTLX[1] Ratings by Major Task[2] Success Status and Experience of FD Failure.

| | Successful (n=7) | | Unsuccessful (n=6) | | FD Failure (n=8) | | No FD Failure (n=5) | |
|---|---|---|---|---|---|---|---|---|
| | M | SD | M | SD | M | SD | M | SD |
| ISA Rating | | | | | | | | |
| Level at 2000 ft plus 60 s | 3.00 | 0.58 | 3.25 | 1.71 | 3.14 | 1.21 | 3.00 | 0.82 |
| NASA TLX Ratings - Build Course to intercept BWZ 208° radial | | | | | | | | |
| Mental Demand | 73.71 | 22.09 | 91.50 | 12.24 | 87.38 | 11.58 | 73.20 | 28.03 |
| Physical Demand | 38.00 | 31.52 | 61.00 | 36.00 | 45.00 | 27.83 | 54.40 | 45.99 |
| Temporal Demand | 80.14 | 12.33 | 85.17 | 21.87 | 81.38 | 16.89 | 84.20 | 18.46 |
| Performance[3] | 34.71[a] | 28.67 | 86.33[a] | 20.66 | 67.88 | 28.17 | 43.60 | 45.57 |
| Effort | 70.86 | 18.72 | 86.00 | 19.52 | 81.25 | 16.31 | 72.40 | 25.73 |
| Frustration | 49.71 | 27.63 | 72.83 | 29.88 | 63.63 | 24.37 | 55.20 | 39.98 |
| Average RTLX rating for event | 57.86 | 18.15 | 80.47 | 19.36 | 71.08 | 14.01 | 63.83 | 31.49 |

[1] Analyses were performed using raw TLX (RTLX) ratings rather than weighted ratings.

[2] The major task to be completed in this high workload event was setting up the aircraft for intercepting the BWZ 208° radial.

[3] Reverse Scored so direction is consistent with all ratings of other subscales (low numerical rating = lower perception of workload demand). With reverse scored performance ratings, low ratings indicate better evaluations of one's performance.

[a] p = .004

Table 12 presents differences among the same four subgroups in their subjective ratings of workload as indicated by the ISA and NASA TLX measures; a MANOVA was again conducted and no significant main effects for success, $F(1,10) = 4.32$, $p = .06$, or FD failure, $F(1,10) = 0.04$, $p = .86$, or interaction between the two were found, Wilk's $\lambda = .76$, $F(3,7) = 0.73$, $p = .57$. Not surprisingly, pilots who successfully accomplished the Event 1 task rated their performance significantly better on the NASA TLX than those who were unsuccessful, $F(1, 11) = 13.40$, $p = .004$.

**Event 2: Reroute and Descent to Meet a Crossing Restriction at a Waypoint**

The second high workload event involved programming and performing a reroute while en route to Martin State. Rerouting the aircraft requires the pilot to remember the new routing instructions from ATC, readback the instructions correctly, and select a strategy to enter the route instructions into their flight plan on the MFD while maintaining situation awareness and control of the aircraft. Imbedded in these tasks is the need to comprehend where the new routing will be taking the aircraft, so pilot knowledge of the location of waypoints and navaids included in the new routing is also required. Clearly, participants who were unfamiliar with the Northeast corridor and the various waypoints and navaids there would be at a disadvantage, even though we allowed all participants as much time as they desired for their pre-flight briefing.

We asked participants to reroute from their original flight path that led from Teterboro, NJ (KTEB) to Martin State Airport (KMTN), just outside of Baltimore, MD. The original routing included in their pre-departure clearance was "Teterboro 6 departure, radar vectors, BIGGY, J75, MURPH, Baltimore direct." When programming in the clearance, the G1000 would have automatically populated all of the intermediate waypoints and navaids between BIGGY and MURPH on J75 on their flight plans: BIGGY, COPES, Modena VOR (MXE), STOEN, SACRI, and MURPH.

In Event 2, when the participants reached COPES, they were contacted by ATC and given the following reroute: "Citation XXXX is now cleared to Martin State Airport via J75, Modena, direct Dupont, Victor 214 to KERNO, direct JUGMO, direct Martin State." Only 18.6 nm separates COPES and MXE, where participants would now need to turn toward the Dupont (DQO) VOR instead of proceeding straight on J75 to STOEN.[2] Further adding to their workload, when participants read the reroute clearance back correctly to ATC, they were provided the additional clearance to "cross Dupont at or below 17,000, maintain 12,000."

The most efficient programming strategy is to quickly input DQO as the waypoint after MXE (MXE should already be in the flight plan). The aircraft will turn when reaching MXE thereby giving the pilot enough time to enter in the rest of the reroute instructions, including the crossing restriction, into the flight plan. Pilots should erase the original waypoints that are no longer appropriate. Presuming that not too much time is required to delete old waypoints and/or add new ones with the crossing restriction, the order in which these two subtasks are accomplished can vary as long as DQO has already been entered in the flight plan so the aircraft makes the required turn at MXE. This strategy optimizes the use of the automation, keeps the aircraft safely within the bounds of the revised ATC instructions, and minimizes the need to hand fly the aircraft.

Most of our participants attempted to use this approach, though with substantial variation in success. Five programmed the reroute and met the crossing restriction without difficulty. The other eight participants experienced a variety of problems including continuing to STOEN or some other waypoint along the original route and/or not making the crossing restriction at DQO. Detailed descriptions of pilot performance of the Event 2 tasks are provided below.

***Overall flight performance during Event 2***. When the pilots were given their reroute instructions they were cruising at an altitude of 20,000 ft MSL and had standard barometric pressure (i.e., 29.92) in the altimeter. Their descent to meet the 17,000 ft crossing restriction at DQO took them through transition altitude and required changing to a local altimeter setting. Although all but two pilots read the barometric information back correctly to ATC, eight participants did not set the barometer to the local setting until quite some time after they passed through the transition altitude, and three did not set it at all during the event. Only two pilots set the barometric pressure before they passed through transition altitude.

***Automation use, flight path management, and the reroute with a crossing restriction***. ATC called to provide the pilots with their reroute instructions as they were crossing COPES and en route to MXE, a distance of 18.6 nm. One professional pilot had significant difficulty with the rerouting and did not cross DQO. ATC repeated the reroute clearance three times before he had it copied correctly, 8.3 nm away from MXE. He then copied the DQO crossing restriction placing him 5 nm and 54 s away from the turn at MXE. Time spent referencing a paper chart and a programming error (entering MXE which was already listed in the flight plan) resulted in his missing the turn to DQO and continuing straight toward STOEN, an error that he did not identify until 20 s later when he was 6.2 nm from STOEN.

Unfortunately, his situation was not that unusual. In our observation, one of the critical factors for correctly navigating the reroute was to quickly enter DQO as the next waypoint. When that was not accomplished quickly, it often set off a chain of delays and mistakes in programming or flying the reroute. Five of the participants did not enter DQO as the next waypoint after MXE until they had already passed MXE and continued toward STOEN. One of the five, a professional pilot, actually arrived at STOEN before turning toward DQO; he traveled 7.5 nm in the wrong direction. It was not until ATC had instructed him to "turn left to 120, direct to Dupont, *now*" that he was able to get back on the correct routing. None of the other four pilots was able to correctly enter all the new waypoints in the reroute instructions though they did eventually arrive at DQO.

The distance from MXE at which participants properly understood the reroute clearance was critical in their ability to enter DQO into their flight plan in time to stay on course. Pilots who had problems entering DQO before arriving at MXE understood the clearance correctly when they were a mean distance of 4.5 nm from MXE. In contrast, the pilots who were able to enter DQO before arriving at MXE understood the clearance correctly at a mean distance of 10.8 nm from MXE.

[2] According to ATC SMEs we consulted during the design phase of this study, 19 nm is about the minimum amount of distance most controllers would require when giving a reroute clearance necessitating a close turn off the original routing.

During the post flight debriefing interview some participants reported having had difficulty hearing ATC instructions and several, including a professional pilot who told ATC that communications were "garbled," requested that all or part of the reroute clearance be repeated. Table 13 shows the distances from MXE where the pilots appeared to correctly understand the reroute clearance and the number of times all or part of the reroute clearance was given. The table shows little difference between owner-operators and professional pilots in their average distance from MXE or the number of times the instructions had to be given. However, there was far less variability for professional pilots, as compared to owner operators in their distance from MXE where they correctly understood the reroute clearance.

An independent samples t-test was performed to test the effect of distance from the turn when the reroute clearance was understood on successfully programming the reroute. Data from three participants were not included in this analysis because the time when the clearance was correctly understood could not be determined or it was never understood correctly. Therefore, the analysis was performed for data from three participants who passed MXE and continued toward STOEN before entering DQO and seven who entered DQO in their flight plans prior to reaching MXE.

The resultant two-tailed t-test was significant, $t(8) = -2.785$, $p = .024$, suggesting that understanding the clearance with ample time to enter it into the flight plan is essential to the orderly management of a flight. However, simply understanding the clearance well ahead of an en route waypoint did not guarantee success. For example, seven of our thirteen pilots had problems with their route of flight because of unwanted waypoints left in their flight plans after programming the new ones for the reroute. As a consequence, they found themselves turning toward at least one unexpected location. Another pilot selected "Direct to" CIROM, a waypoint which was not part of either the original or revised clearance instructions.

Table 13. Correctly Copying Reroute Clearance.

| | Number of times instructions were given | | | | | Distance from MXE (nm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Min | Max | SD | Mean | Median | Min | Max | SD |
| Owner-operator | 2.29 | 2 | 1 | 3 | 0.76 | 9.67 | 11.20 | 0.60 | 16.10 | 5.32 |
| Professional | 3.17 | 3 | 2 | 5 | 1.17 | 8.28 | 8.30 | 8.00 | 8.50 | 0.21 |
| Overall | 2.69 | 3 | 1 | 5 | 1.03 | 9.20 | 8.50 | 0.60 | 16.10 | 4.20 |

Table 14. Errors Committed During Event 2.

| | All Participants (n = 13) | Owner-Operators (n = 7) | Professional Pilots (n = 6) |
|---|---|---|---|
| Did not cross DQO | 1 | 0 | 1 |
| Programmed DQO after passing MXE | 5 | 3 | 2 |
| Did not enter all the new waypoints in the reroute | 4 | 1 | 3 |
| Left incorrect waypoints in flight plan | 7 | 4 | 3 |
| Entered a waypoint not part of the reroute | 1 | 1 | 0 |
| Did not meet crossing restriction at DQO and did not inform ATC of that fact | 4 | 2 | 2 |
| Communication/Readback errors[1] | 29 | 16 | 13 |
| Total number of errors | 51 | 27 | 24 |
| Average number of errors per participant | 3.92 | 3.86 | 4.00 |

[1] Communication or readback errors committed by all 13 participants.

The errors identified during the second event are summarized in Table 14. A one-way ANOVA revealed no significant differences in the number of errors committed by owner-operators as compared to professional pilots, $F(1,11) = 0.001$, $p = .97$.

Participants who encountered problems with the reroute adopted a variety of strategies, sometimes more than one, for getting back on course. Four participants requested delaying vectors and went off course while they sorted out reroute programming issues. Four pilots selected "Direct to" DQO, though one had to select that function twice because his first selection dropped out when he momentarily switched from NAV(GPS) to HDG mode. Three others also switched to HDG mode to get turned to a waypoint and two disconnected the AP entirely and flew manually for a time to get headed in the right direction. Thus, the strategy for these participants was to simplify the tools they were using and engage a "lower level" of automation (or none at all). No one appeared to reduce their airspeed to gain more time.

The second part of the reroute clearance included a crossing restriction of 17,000 ft MSL or below at DQO and then maintain 12,000 ft MSL. One of the methods for flying a descent is to use the vertical path autopilot mode (VPTH). The VPTH profile optimizes the descent rate to meet a specified altitude at a particular waypoint, making it ideal for meeting the crossing restriction at DQO. The pilot must select the desired waypoint, enter the required altitude, and press the VNV button on the autoflight control system (AFCS) panel.

Four of the pilots programmed a VPTH descent but one of them only used it to provide guidance information and flew the descent using VS mode. This participant had significant difficulty managing the reroute however, and he failed to make the crossing restriction at DQO. Of the nine other pilots, all of whom used VS mode, three also failed to make the crossing restriction at DQO. The mean altitude at DQO of those who did not make the crossing restriction was 18,725 ft MSL ($SD$ = 853 ft MSL); one pilot crossed DQO at nearly 20,000 ft MSL. None of the four participants who failed to make the crossing restriction contacted ATC to let them know.

Table 15. Descent Performance in Event 2.

| Pilots and Behaviors | | | | Means | | | |
|---|---|---|---|---|---|---|---|
| Flew VNAV Profile | Met Crossing Restriction | Exceed Speed | Number of Pilots | Descent Rate | DQO Crossing Altitude | Descent Airspeed | Speed Difference |
| No | Yes | No | 3 | -1267 | 14902 | 216 | 5 |
| No | Yes | Yes | 3 | -1900 | 9778 | 248 | 39 |
| No | No | -- | 6 | -1583 | 12340 | 232 | 22 |
| No | No | No | 1 | -1100 | 19999 | 154 | -55 |
| No | No | Yes | 3 | -3817 | 18300 | 237 | 25 |
| No | No | -- | 4 | -3138 | 18725 | 217 | 5 |
| Yes | Yes | No | 2 | -2500 | 16962 | 211 | 3 |
| Yes | Yes | Yes | 1 | -2000 | 17115 | 239 | 30 |
| Yes | Yes | -- | 3 | -2333 | 17013 | 220 | 12 |

Table 15 shows the descent performance of the pilots in our study. The six pilots who used VS and made the crossing restriction did not just meet the requirement but had descended to a mean altitude of 12,340 ft MSL at DQO, preparing them for the rest of the journey to the Martin State Airport. On average, these pilots flew the descent more quickly, though a lower percentage of them had disproportionate speed (i.e., 10 KIAS or more over speed at cruise), compared to those who did not meet the crossing restriction.

Programming strategies used by participants for the Event 2 tasks varied considerably. Some entered DQO first and then erased non-pertinent waypoints from the original clearance before entering in the rest of the new waypoints. Others programmed the VPTH descent after entering DQO and then followed by entering the rest of the reroute and deleting non-pertinent waypoints. Sometimes the entire reroute was entered before programming to meet the crossing restriction or deleting old waypoints.

Table 16. Time Required for Programming Reroute and Descent to Meet the DQO Crossing Restriction.[1]

| | All Participants | | | Owner-Operators | | | Professional Pilots | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Total time required for programming (did not interleave other tasks) | 2 | 0:02:20 | 0:00:45 | 1 | 0:02:52 | N/A | 1 | 0:01:48 | N/A |
| Total time required for programming (did interleave other tasks) | 5 | 0:03:31 | 0:01:28 | 3 | 0:03:21 | 0:01:49 | 2 | 0:02:57 | 0:01:28 |

[1] Times were determined using data only from those participants who had successfully completed all reroute and descent programming, including deleting old waypoints, by the time they had reached DQO.

Table 16 presents the mean amounts of time it took for participants to program Event 2 subtasks: enter DQO, program VPTH (if they used it), input the remaining reroute waypoints, delete old waypoints, and press VNV to activate VPTH (if they used it).

As would be expected, on average those who interleaved other tasks while programming (range = 01:33 to 05:04) took more time to complete the programming than those who did not (range = 01:48 to 02:52). Interestingly, one owner-operator who used VPTH interleaved other tasks and was the fastest in completing all of the Event 2, programming at 01:33.

***Aircraft and FAR limitations***. At no point in time did any participant exceed any aircraft or FAR limitations during the second event although two owner-operators did come close to $V_{mo}$ (250 KIAS) for a period of time (247 KIAS and 249 KIAS).

***Checklist and chart usage***. Only one pilot was observed using a checklist (most likely the descent checklist) and another pilot was heard verbalizing the status of the autopilot, though no checklist was visible. The other pilots were observed with something in their lap or on the seat next to them, which may have included a checklist, though it could not be confirmed through the video.

As for charts, the one owner-operator and three professional pilots who were unable to successfully enter the full flight plan into the MFD used paper charts while the rest ($n$ = 9) made extensive use of the navigation maps that are part of the G1000 MFD. Of those using the MFD charts, five were able to complete programming the reroute at a mean distance of 8.46 nm from DQO. Only one of these participants, a professional pilot, completely entered the reroute and deleted all unwanted waypoints before reaching MXE. That pilot was at a distance of 19.1 nm from DQO by the time his route was completely edited. The remaining four entered the reroute clearance but made errors such as failing to delete waypoints from the original clearance or neglecting to enter JUGMO

Table 17. Pilot Demographics by Problems Encountered With the Reroute or Meeting the Crossing Restriction at DQO.

| | | Reroute | | | | Crossing Restriction at DQO | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Problems (n=7) | | No Problems (n=6) | | Did not Meet (n=4) | | Met (n=9) | |
| | | M | SD | M | SD | M | SD | M | SD |
| Age | | 49 | 12.65 | 48.83 | 7.55 | 48.75 | 11.70 | 49.00 | 10.21 |
| General Flying Hours | Total | 3918.57 | 2510.00 | 4092.67 | 1697.69 | 2525.00 | 1789.55 | 4654.00 | 1941.32 |
| | Past year | 245.29 | 163.74 | 213.33 | 151.78 | 196.00 | 99.84 | 245.89 | 174.13 |
| | Past 3 months | 48.57 | 29.26 | 57.33 | 33.49 | 43.75 | 21.75 | 56.56 | 33.76 |
| | Single pilot jet | 273.57[a] | 143.02 | 399.33[a] | 474.96 | 476.25[b] | 579.76 | 267.33[b] | 146.86 |
| Citation Specific Hours | Past year | 178.29 | 110.15 | 125.00 | 53.68 | 123.25 | 23.14 | 167.22 | 105.72 |
| | Single pilot in past year | 167.86 | 117.40 | 104.17 | 68.82 | 73.75 | 44.23 | 167.22 | 105.72 |

[a] p <.001 but becomes p = .16 when data from an outlier is removed (new Ms and SDs in text)
[b] p <.001 but becomes p = .14 when data from an outlier is removed (new Ms and SDs in text)

***Pilot behavior and general workload management*.** Table 17 shows the flight experience of participants relative to encountering problems in accomplishing the reroute and meeting the crossing restriction at DQO.

A MANOVA revealed no significant interaction effect between problems or success with the reroute and the crossing restriction related to age or any type of flying history, Wilk's $\lambda = .07$, $F(7,3) = 5.68$, $p = .91$. However, significant main effects were found for both tasks associated with the total number of single-pilot hours in a jet the participants had accrued (reroute task: $F(1,9) = 38.81$, $p < .001$ , partial $\eta^2 = .81$; crossing restriction: $F(1,9) = 35.35$, $p < .001$, partial $\eta^2 = .80$). Although when we examined the means in Table 16, it appeared that participants who did *not* make the crossing restriction at DQO actually had significantly more hours of flight time as single jet pilots than those who were successful in making the crossing restriction, contrary to what one would expect. Further analysis indicated that one participant who had no problems with the reroute but did not make the crossing restriction had accrued an exceptionally high number of single jet pilot hours as compared with the rest of the sample. When data from this outlier are removed, the mean number of single-pilot jet hours of those who had no difficulties with the reroute falls to 210.20 hrs. ($SD = 117.05$ hrs.) and the mean single jet pilot hours of those who did not make the crossing restriction falls to 186.67 hrs. ($SD = 32.15$ hrs.). Without the data from this outlier, the significant main effects found for both the reroute and the crossing restriction relative to single jet pilot hours disappear (reroute task: $F(1,9) = 2.40$, $p = .16$ ; crossing restriction: $F(1,9) = 2.59$, $p = .14$).

Table 18. RTLX Workload Ratings for Event 2.

| | Flew Correct Path (n=6) | | Flew Incorrect Path (n=6) | | Owner-Operator (n=6) | | Professional (n=6) | |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| NASA TLX Ratings - Reroute and descent to meet a crossing restriction at a waypoint | | | | | | | | |
| Mental Demand | 50.83 | 17.42 | 55.67 | 26.98 | 54.67 | 27.81 | 51.83 | 16.34 |
| Physical Demand | 39.50 | 22.47 | 21.50 | 17.47 | 18.67 | 5.20 | 42.33 | 25.33 |
| Temporal Demand | 47.33 | 26.03 | 44.50 | 33.31 | 38.33 | 34.47 | 53.50 | 21.58 |
| Performance | 28.83 | 31.30 | 55.83 | 41.37 | 45.00 | 40.80 | 39.67 | 38.04 |
| Effort | 54.83 | 16.39 | 58.00 | 30.05 | 57.83 | 24.73 | 55.00 | 23.68 |
| Frustration | 36.33 | 25.22 | 44.67 | 29.92 | 37.50 | 32.39 | 43.50 | 22.42 |
| Average RTLX Rating for Event | 42.94 | 19.73 | 46.69 | 22.24 | 42.00 | 23.61 | 47.64 | 17.77 |

We submitted the RTLX workload ratings for the reroute and descent to meet a crossing restriction (see Table 18) to a within-subjects repeated measures ANOVA to determine if any construct represented by the TLX subscales was of particular importance to performing the task. More specifically, we expected mental demand ratings to be higher than those for physical demand. Also, since the reroute instructions had to be entered in a timely manner, the temporal demand subscale was also expected to be higher as an indicator of time pressure. However, using a Greenhouse-Geisser correction, no significant differences were found across the TLX subscales for this task, $F(2.334, 25.677) = 2.64$, $p = .083$.

Six of the 13 pilots were seen making visible gestures and vocalizations indicative of frustration and high workload while they were receiving the reroute instructions. For example, an owner-operator was only 0.6 nm before reaching MXE when he appeared to understand the reroute clearance. He then used paper charts to locate the waypoints rather than enter them into the flight plan, suggesting his need to understand the changes to his routing before accepting it. Due to the delay, he ended up off course and accommodated by switching to HDG mode but overshot DQO. His frustration was readily apparent. Other pilots could be heard mumbling or groaning or saying, "This is really high workload," calling ATC several times for clarification, or requesting delaying vectors because he was "having trouble getting all this." It was clear that at least four of the 13 demonstrated behavior that indicated their workload was high.

**Event 3: Expedited Descent**

The third major event occurred approximately 18 minutes after the second leg began as the pilots were climbing to 12,000 ft MSL from 2,000 ft MSL, with traffic converging on their location. The traffic in our scenario was an A320 with an emergency descending to land at Dulles International Airport. When the participants reached approximately 7000 ft MSL during their climb, ATC instructed them to "descend immediately and maintain 6000 feet for emergency traffic." We were interested in observing the pilots' behavior and performance during this situation. Key to that was assessing the speed with which they complied with the instruction to initiate a descent, the amount of altitude gain before a descent was initiated, the technique used to descend, and the possible role or use of automation during their descent. For example, did the pilots quickly disengage the autopilot and get clear of the emergency traffic or did they try to use the automation to descend to the new assigned altitude?

Twelve of the participants initially disengaged the automation to initiate the expedited descent and all participants generally completed the task successfully although some errors were noted. Detailed descriptions of the findings for this event follow.

***Automation use, flight path management, and the expedited descent***. As with the other events, autopilot use was common throughout this segment. Prior to ATC calling with the clearance to climb from 2,000 ft MSL (before the start of Event 3), all 13 of the pilots were using ALT Hold mode; 12 of those pilots were using NAV(GPS) mode to maintain their heading with

the remaining pilot using ROLL mode. The climb to 12,000 ft MSL was accomplished using FLC by nine of the pilots and the other four used VS.

Once the expedited descent instruction came, 12 of the 13 pilots disconnected the autopilot and began the expedited descent manually. The remaining pilot reset his ALT reference window to 6000 feet and used VS with an 1800 fpm descent. While descending, seven re-engaged the autopilot. Of those seven, four used VS (median 1,800 fpm descent, range 1,500 to 3,100 fpm descent), and three of the pilots also dialed 6,000 in the altitude reference window and used ALTS. The pilots did not make any changes to their lateral modes during this descent. Table 19 summarizes the vertical and lateral modes used at each of the stages of the expedited descent procedure. Additionally, Table 20 shows the stages of the flight at which the autopilot was re-engaged.

Table 19. Autopilot Modes Used During Expedited Descent.

| | Level at 2000 ft | Climbing to 12,000 ft | Expedited Descent | Maintain 6,000 ft/ |
|---|---|---|---|---|
| Vertical Modes | | | | |
| ALT HOLD | 13 | | 1 | 11 |
| FLC | | 9 | | |
| VS | | 4 | 7 | |
| Manual Flt. | | | 5 | 2 |
| Lateral Modes | | | | |
| NAV(GPS) | 12 | 13 | 8 | 11 |
| ROLL | 1 | | | |
| Manual Flt. | | | 5 | 2 |

Table 20. Timing of Autopilot Re-Engagement.

| | |
|---|---|
| Does not Turn off, uses AP for Descent | 1 |
| During Descent | 7 |
| At Level-off at 6,000 ft | 3 |
| When Resuming Climb back to 12,000 ft | 2 |

Table 21. Time Lapsed for Participant Response and Altitude Gained Prior Aircraft Descent.

| | Mean | Min | Max | SD |
|---|---|---|---|---|
| Time Lapsed (seconds)[1] | | | | |
| All Participants | 1.85 | -2 | 5 | 2.34 |
| Owner Operators | 2.86 | 1 | 5 | 1.77 |
| Professional Pilots | 0.67 | -2 | 5 | 2.5 |
| Altitude Gained (ft) | | | | |
| All Participants | 273.58 | 39.88 | 601.31 | 155.05 |
| Owner Operators | 260.84 | 155.86 | 376.43 | 72.49 |
| Professional Pilots | 288.44 | 39.88 | 601.31 | 225.61 |

[1] Negative time indicates that the pilot was taking action before ATC finished providing instructions to expedite a descent.

During an expedited descent, the goal of the pilot is to get down to the required altitude as quickly and as safely as possible. Thus, we were interested in two primary aspects related to how this was achieved: 1) the amount of time that elapsed and the amount of altitude gained from when ATC gave the instruction to descend until the aircraft actually began to descend, and 2) how quickly and precisely the descents occurred. Table 21 presents findings related to the first aspect: how long it took for pilots to initiate a response (timed from the end of the ATC instruction to descend) and how much altitude was gained before the aircraft started to descend (again, timed from the end of the ATC call to the pilot).

As can be seen in Table 21, some participants initiated a response (often disengaging the AP) before the end of the radio call from ATC. Also evident in the table is the large range of altitudes gained by pilots following the radio call before the aircraft started down. This large range was primarily due to one professional pilot who did not disengage the AP during the descent. In the time it took him to reset his ALT reference window to 6000 ft MSL, select VS with an 1800 fpm descent, and for the aircraft to actually stop climbing, he had gained 601.31 ft. Excluding his data, the other professional pilots gained an average of 225.86 ft MSL (*SD* = 185.09 ft MSL, range = 39.88 ft MSL to 494.30 ft MSL) before their aircraft started to descend.

Although turning the AP off and manually initiating the descent clearly reduced the amount of altitude gained prior to descent, it was unclear if continuing to fly manually or re-engaging the AP during the descent had any effect on the second expedited descent aspect of interest: how quickly and precisely the descent was flown. To test this, the descent durations of pilots who used the autopilot were compared with the descent durations of those who flew the descent manually using an independent samples t-test. For the purpose of this analysis, data from two pilots were first removed from the sample. One was removed because he never disabled the autopilot. The second was removed because, due to an ATC error, he had very little time to make a descent before the traffic was at his position. This resulted in a group of six participants who re-engaged the autopilot during their descent and five who did not.

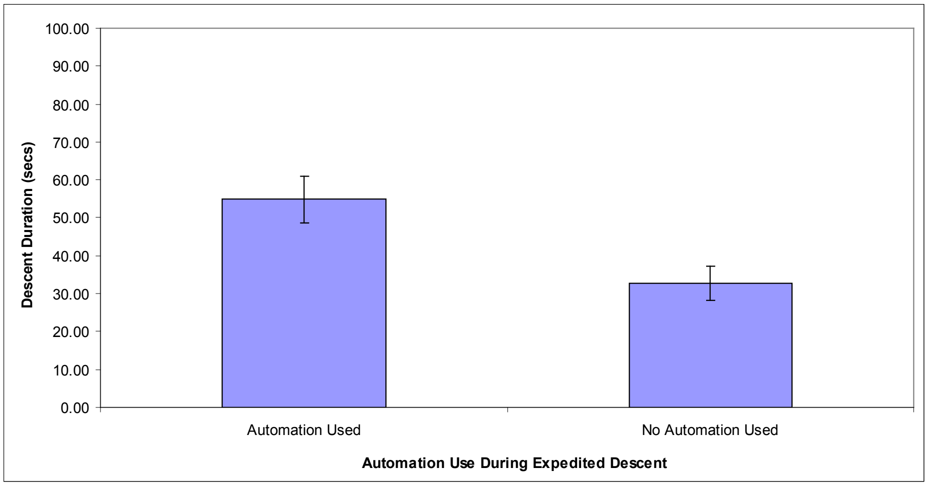



*Figure 17.* Time Required to Complete Expedited Descent as a Function of AP Use.

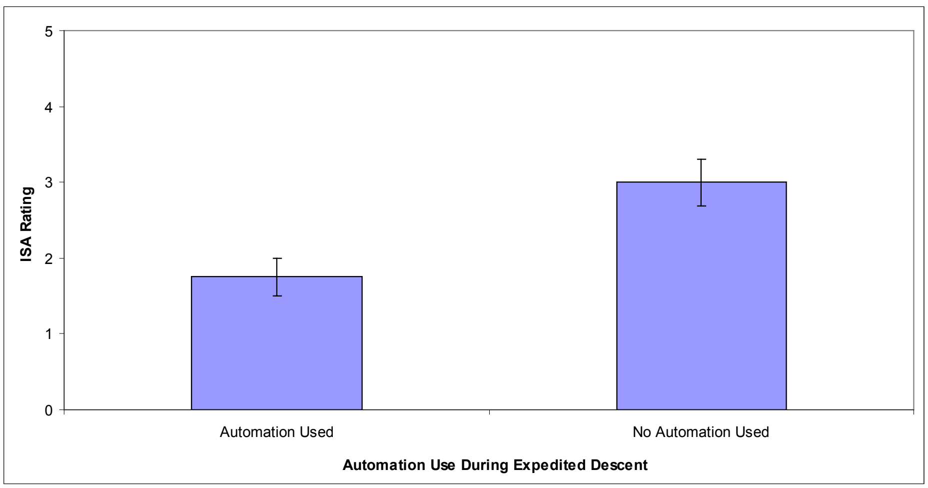



*Figure 18.* ISA Workload Rating During the Expedited Descent as a Function of AP Use.

It was found that re-engaging the autopilot ($M$ = 54.83, $SD$ = 15.2) during the descent significantly increased the time it took to make the descent versus disabling the autopilot and descending manually ($M$ = 32.80, $SD$ = 10.32, $t(9)$ = 2.75, $p$ = .022; see Figure 17). Although this result suggests a decrement related to automation use, it did not help us to evaluate workload as a function of automation use during the expedited descent. To determine that we used an independent samples t-test for the ISA ratings made when the aircraft reached 6,000 ft MSL following the descent. Again, there was a significant effect ($t(7)$ = 0.21, $p$ = .21); the ISA ratings for those who re-engaged the autopilot were lower ($M$ = 1.75, $SD$ = 0.5) than the ISA ratings of pilots who hand flew the descent ($M$ = 3, $SD$ = 0.71) indicating a perception of significantly lower workload by those who re-engaged the autopilot (see Figure 18). Therefore, re-engaging the autopilot during the descent resulted in an increased mean time to achieve the descent by 40%, but doing so significantly decreased perception of workload.

Although, on average, the five participants who flew the entire descent manually achieved their descents more quickly, the accuracy with which they flew suffered as compared to those who re-engaged the AP. Three participants flew through the 6000 ft MSL level-off by an average of 286.67 ft MSL and another briefly exceeded $V_{mo}$ by a few kts. twice during the descent. Thus, our study found a speed versus precision tradeoff with regard to AP use once the expedited descent began. From an operational perspective, it is hard to say which is of greater importance. SMEs who we have consulted have suggested that as long as an expedited descent is initiated quickly, the accuracy of flying the descent may be of greater importance and advocate using automation even if it lengthens the amount of time required to arrive at the descent altitude.

***Pilot and aircraft performance***. All pilots correctly acknowledged and read back the instructions to climb to 12,000, at which time they were instructed to contact Potomac Departure on frequency 124.55. All pilots were successful in making the required frequency change and making contact with the new controller. However, during Event 3, four participants made a readback or some other communication error.

***Aircraft and FAR limitations***. As mentioned earlier, one pilot briefly exceeded $V_{mo}$ while hand-flying the descent. The excess speed took place in two back-to-back periods. The first lasted for 1.4 s and reached a maximum speed of 251 KIAS. That was followed by a 10 s period where the participant pitched the aircraft up to reduce airspeed to 244 KIAS. The pilot then pitched back down to continue his descent and retarded the

thrust levers. However, he again exceeded the speed limitations of the aircraft for 5.4 s and reached a maximum speed of 252 KIAS. No other participants exceeded aircraft or FAR limitations during Event 3.

***Checklist and chart usage***. There did not appear to be any checklist and/or chart usage during the expedited descent and none was expected. Pilots appeared to be primarily concerned with descending to the instructed 6,000 foot altitude as quickly as possible and using a checklist could have created a lag in participants' ability to avoid emergency traffic. A Citation Mustang emergency checklist labeled "Emergency Descent" does exist; however, none of our participants used it or appeared to have completed the memory items from it. This checklist is written to expedite descent to a lower altitude, typically due to a pressurization problem, rather than simply to get quickly out of the way of another aircraft.

***Pilot behavior and general workload management***. The RTLX ratings for the expedited descent procedure are summarized in Table 22. Recall that, after reverse-scoring the performance scale for consistency in directionality with the other scales, a lower score indicates lower perceived workload and higher perceived performance.

The ratings indicate that the pilots perceived a high temporal demand during the expedited descent. This is to be expected because the objective was for pilots to get out of the way of the emergency traffic as quickly as they could safely manage. The low performance scores indicate that the participants felt they had performed the expedited descent quite well; this is consistent with their relatively low levels of frustration. The other subscales are roughly equivalent in terms of the average score. These results, taken together, indicate that pilots thought that the task was relatively easy to accomplish without any significant mental demand, physical demand, or extraordinary effort.

As before, we submitted the RTLX data to a within-subjects repeated measures ANOVA to determine if one or more of the constructs represented by the TLX subscales was of particular importance relative to performing an expedited descent. The design of the ANOVA was the same as described earlier. The ANOVA was found to be significant, $F(5, 60)=9.902, p < .000$, partial $\acute{\eta}^2 = .452$.

Pairwise comparisons were conducting using a Bonferroni correction to control for family-wise error inflation. We found that Performance was ranked significantly lower (where lower scores indicate better performance) than Mental Demand ($p = .002$), Temporal Demand ($p < .000$), and Effort ($p = .014$). Also, Temporal Demand was significantly higher than Frustration ($p = .019$). This confirms that participants believed they had performed the expedited descent well and did not find the task to be particularly demanding but were aware of the need to complete it quickly. The mean ISA rating for the event was 2.55, indicating a low to fair level of workload (Castle & Leggatt, 2002), which is consistent with the RTLX workload ratings.

**Event 4: Communication assistance for a lost pilot**

Prior to the initiation of this fourth high workload event, pilots were presented with an abnormal condition, a circuit breaker (cb) pop accompanied with an amber alert message "ANTISKID FAIL." Although this occurred 30 nm before the start of Event 4, we expected that some pilots might still be considering this condition and could possibly be referring to the abnormal checklist for an antiskid failure or landing tables when Event 4 began.

High workload Event 4 began approximately three-quarters of the way through the second leg of the experimental flight, as the participants were crossing WITTO level at 16,000 ft MSL, when ATC gave them the following instruction: "Descend pilot's discretion, cross 15 northeast of Montebello at one-zero, 10,000." Thirteen nautical miles past WITTO, as participants were crossing MITRE, a "lost pilot" in another aircraft, played by one of the researchers, was heard on the radio having difficulty

Table 22. Pilot Participant TLX-Ratings of the Expedited Descent Procedure.

| | Owner-Operator (n=7) | | Professional (n=6) | | All (n=13) | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| NASA TLX Ratings - Expedited Descent | | | | | | |
| Mental Demand | 52.86 | 31.01 | 48.33 | 22.60 | 50.77 | 26.44 |
| Physical Demand | 38.14 | 29.74 | 50.00 | 33.07 | 43.62 | 30.59 |
| Temporal Demand | 60.57 | 37.67 | 83.67 | 15.67 | 71.23 | 30.91 |
| Performance | 15.57 | 8.10 | 19.33 | 10.52 | 17.31 | 9.10 |
| Effort | 44.86 | 34.43 | 68.33 | 17.82 | 55.69 | 29.55 |
| Frustration | 24.29 | 22.98 | 39.17 | 21.01 | 31.15 | 22.53 |
| Average RTLX Rating for Event | 39.38 | 19.63 | 51.47 | 11.01 | 44.96 | 16.81 |

[1] Reverse-scored so that low scores indicate perceived high performance.

communicating with ATC. The lost pilot was VFR and trapped under a thick cloud deck looking for a place to land. After several transmissions from the Center controller and the lost pilot, it was clear that the lost pilot could hear the controller but the controller could not hear the lost pilot. The controller then asked the participant pilots if they could hear the lost pilot on the frequency and if they would be willing to transmit communication from the lost pilot to ATC. Although our participants could have declined the request for assistance, none chose to do so. Three owner-operators and three professional pilots even offered assistance before they were asked. Event 4 ended at the conclusion of the lost pilot scenario, which occurred just prior to the approach and landing at KHSP.

During Event 4, the participants needed to adhere to the instruction to descend when desired to meet a crossing restriction 15 nm prior to a VOR, in addition to helping to facilitate the communication from the lost pilot. Unlike meeting the crossing restriction at Dupont in Event 2, this clearance required that the participants identify an unmarked point on the navigation charts (i.e., not a predefined waypoint or VOR) at which to meet the crossing restriction and to determine when they wanted or needed to initiate their descent to meet it. Furthermore, during the "lost pilot scenario" it was also expected that participants would also need to check or verify the weather conditions at KHSP and set up the cockpit in preparation for the approach at KHSP. Thus, even though the approach and landing at KHSP occurred just after high workload Event 4 ended, aspects of participants' approach and landing performance that could have been influenced by tasks within Event 4 were also subjected to analysis.

Four of the 13 pilots had some sort of difficulty in programming the crossing restriction or in descending, but only one actually failed to make the crossing restriction. Approximately half ($n$ = 6) had some sort of problem associated with programming or flying the precision approach at KHSP. Detailed findings related to pilot performance during Event 4 are described below.

***Overall flight performance during Event 4.*** Almost all pilots reported during post-flight debriefings that the second leg of the experimental flight involved less workload than the first. However, it should also be noted that no unscripted FD failures occurred during the second leg. As mentioned above, the timing and analyses for high workload Event 4 began with the call from ATC and their crossing WITTO. High workload Event 4 ended when ATC handed the participant pilots off to another controller at the end of the lost pilot scenario which generally occurred around the time participants crossed MOL. Event 4 lasted an average of 7 min and 55 s($SD$ = 31 s, range = 0:07:11 to 0:08:53).

Although at least one error was committed by each of the participants during Event 4 or during the approach into KHSP, they generally flew within appropriate parameters. For example, all participants maintained engine ITT below the limit of 830° and responded to all radio calls from ATC. Twelve pilots met the crossing restriction, and no excessive bank angles, yaw, or unusual attitudes were observed. All participants flew close to $V_{mo}$ (250 KIAS) during the event and their airspeeds ranged from 193 KIAS ($M$ = 210.85 KIAS, $SD$ = 14.51 KIAS) to 248 KIAS ($M$ = 243.23 KIAS, $SD$ = 4.36 KIAS) with an overall average airspeed of 228.30 KIAS ($SD$ = 8.80 KIAS). Those flying slower airspeeds tended to be participants who reduced their speeds purposefully near the end of the lost pilot scenario to increase the amount of time they had available to finish preparing for the approach at KHSP.

With regard to communications with ATC during Event 4, 12 participants used only the Com 1 radio and one participant used only the Com 2 radio; however, all participants had the CTAF and ASOS frequencies for KHSP dialed into the other radio. No one had the emergency frequency (121.5) dialed into either radio. The only time participants were instructed to change frequencies to contact a new controller marked the end of Event 4.

The observable errors committed during the event or the approach to KHSP can be seen in Table 23. One professional pilot committed only one error when he neglected to report the initiation of his descent from 16,000 ft to ATC; all other participants made two or more errors during the event.

A one-way ANOVA revealed no significant differences between owner-operators and professional pilots with regard to the number of errors committed during Event 4 and the approach to KHSP, $F(1,11) = 0.54, p = .48$. However, two surprising findings were the large number of pilots who neglected to contact ATC to report they had initiated their descent from 16,000 ft MSL ($n$ = 10) and the large number who landed at KHSP with an incorrect altimeter setting ($n$ = 8).

***Automation use, flight path management, and accomplishment of Event 4 tasks***. All participants typically made G1000 inputs without hesitation. The AP and FD were used by all participants throughout the event from beginning to end. All pilots used NAV(GPS) mode throughout Event 4 with the exception of one professional pilot who switched to HDG mode at the very end of the event when he requested to stay on his current heading (rather than turn to the initial approach fix [IAF]) to gain some time to complete preparation for the approach. Other lateral modes used by some participants during the approach (after Event 4 had ended) will be described later. Two different vertical modes (VPTH and/or VS) were used by participants to descend to meet a crossing restriction in Event 4 and are discussed below.

There were three major high workload tasks to be accomplished during, and just after, Event 4: 1) meet the crossing restriction, 2) assist lost pilot communications, and 3) execute the approach at KHSP. The lost pilot scenario ended very close to the point where participants would be turning toward the IAF for the approach at KHSP, so we were interested in how the tasks in Event 4 may have influenced participants' preparation and execution of the approach.

Table 23. Errors[1] Committed During High Workload Event 4.

| | All Participants (n=13) | Owner-Operators (n=7) | Professional Pilots (n=6) |
|---|---|---|---|
| Communication/readback errors[2] | 4 | 1 | 3 |
| Did not report when leaving 16,000 ft MSL for 10,000 ft MSL[3] | 10 | 6 | 4 |
| Minor error when programming the crossing restriction | 1 | 1 | 0 |
| Substantial error(s) when programming the crossing restriction | 4 | 2 | 2 |
| Failed to make crossing restriction | 1 | 0 | 1 |
| Misunderstood ATC/lost pilot communication capabilities[4] | 5 | 4 | 1 |
| Minor error when programming the ILS rwy 25 approach at KHSP | 1 | 0 | 1 |
| Substantial error(s) when programming the ILS Rwy 25 approach at KHSP | 7 | 4 | 3 |
| Landed at KHSP with incorrect altimeter setting | 8 | 3 | 5 |
| Total errors | 41 | 21 | 20 |
| Mean number of errors | 3.15 | 3.00 | 3.33 |

[1] "Errors" includes only those that were observable and does not include some difficulties with flight path management described elsewhere in this report.

[2] Communication or readback errors committed by 4 participants

[3] One participant, a professional pilot, did report late at around 15,000 ft MSL

[4] Participant had difficulty understanding that the "lost pilot" could hear ATC but that ATC could not hear the lost pilot—the participant needed to transmit comms from the lost pilot to ATC but did not need to transmit comms from ATC to the lost pilot.

In our review of participant performance of these three major tasks, we first turn our attention to the ways in which participants handled the instruction from ATC to begin a descent from 16,000 MSL, at a time of their choosing (i.e. “at their discretion”), so that they were at 10,000 ft MSL 15 nm prior to reaching the MOL VOR. This clearance was given by ATC when the participants were 44 nm from MOL (29 nm from the point where they had to meet the crossing restriction). Participants began their descents when they were an average of 32.96 nm (SD = 4.44 nm) from MOL (about 18 nm from the crossing restriction point) and were traveling an average of 224.69 KIAS (*SD* = 10.21 KIAS).

Twelve of the 13 participants programmed VPTH to accomplish this task although two of them did not couple VPTH to the AP and just used its guidance to support their descent using VS (one of them did not make the crossing restriction—was 1,180 ft high). Additionally, VPTH did not capture for one participant because he forgot to change the target altitude in the altitude reference window on the PFD so he ended up using VS instead. The remaining participant used VS with no VPTH guidance as a back-up.

It took the 12 participants an average of 53 s (*SD* = 42 s; range = 00:20 to 02:09) to program the VPTH descent although there were two distinct clusters of time it took to do this programming. These clusters appeared unrelated to participant subgroup (owner-operator or professional pilot) or whether the VPTH was used for the descent or only for back-up information. The participants with the lowest programming times (*n* = 8, range = 20 to 38 s) took an average of 29 s (*SD* = 7 s) to do so; those with the longest programming times (*n* = 4, range = 01:35 to 02:09) took an average of 1 min 58 s (*SD* = 10 s) to complete the programming. As expected, those taking more time to complete the programming interleaved other tasks while doing so.

One of the four participants who used VS for the descent set just one descent rate (1700 fpm). The other three set an initial descent rate (1,500 to 2,500 fpm) and increased it 500 to 600 fpm during the descent. One participant who unsuccessfully used VS with VPTH guidance chose an initial descent rate of 2,500 fpm and continued to fly close to $V_{mo}$. When it started to become apparent that he might not make the crossing restriction, he compensated by pulling back some power but waited almost a minute before increasing his descent rate to 3,000 fpm (passing through 12,700 ft MSL 2.58 nm from the crossing restriction point). Although it seemed clear that the participant knew he had not met the crossing restriction, he did not inform ATC. Two pilots, including the one who was unsuccessful, initially made an error when programming VPTH by placing the point where the crossing restriction was to be met 15 nm past MOL instead of 15 nm before MOL. Both caught their errors fairly quickly and corrected them.

The second major task of Event 4 involved assisting with transmitting communications from a lost VFR pilot to ATC. Due to problems with the simulator audio system, one participant was not presented with the lost pilot scenario during leg 2. As mentioned earlier, all the other participants agreed to assist and six volunteered before ATC could even ask. All the participants continued to offer assistance until the situation had been resolved with the exception of one who did not transmit the final two comms from the lost pilot to ATC because he was preparing for his approach into KHSP. Five participants had at least some initial confusion as to who could hear whom during the scenario; in those cases, the lost pilot clarified that she could hear ATC and only one participant continued to transmit ATC comms to the lost pilot, in addition to lost pilot comms to ATC, throughout the scenario.

The lost pilot situation was typically resolved about the time that participants crossed MOL, which is 17.3 nm from the IFAVU IAF for the ILS or LOC RWY 25 approach into KHSP (see Figure 19). Some participants appeared to become a bit concerned about being ready for the impending approach into KHSP during the lost pilot scenario, and five did such things as slow down or ask for vectors or some other alternate routing that would give them added time to prepare (e.g., stay on current

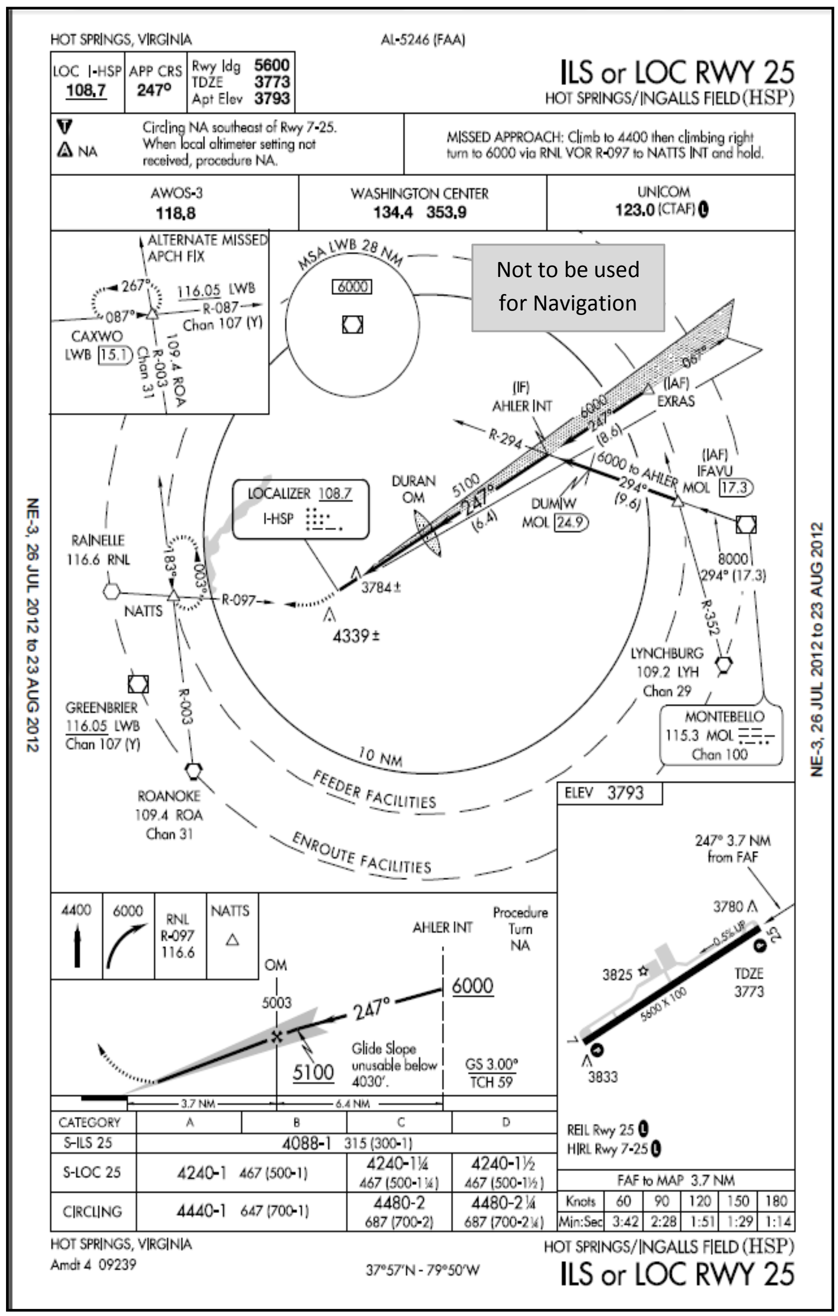



*Figure 19.* ILS or LOC RWY 25 Approach to KHSP (AOPA, 2012).

heading a bit longer past MOL, requested the EXRAS IAF which was 5 miles further away from MOL, etc.). Contrary to what was expected, most pilots did not actively engage in preparing for the approach during the lost pilot scenario. Three did query ATC about aspects of the approach while assisting with the lost pilot comms (e.g., which approach could be expected), and one was observed looking at aircraft weights on the MFD; however, very little of their preparation for the approach occurred during the lost pilot scenario. The other nine participants were not engaged in any observable approach preparation during the scenario.

Further analysis revealed that six pilots (three owner-operators and three professional pilots), including two who queried ATC during the scenario, had actually completed most or all of their approach preparations (e.g., reviewing/briefing the approach) before Event 4 or the lost pilot scenario began. Additionally, six participants were observed entering in the KHSP CTAF and ASOS frequencies into the radios quite early during the leg (e.g., before they departed KMTN, on climb out from KMTN).

Four participants briefed the approach (i.e., reviewed the approach plate for the first time) between MOL and the IAF, and one professional pilot briefed the approach very late, just before arriving at the AHLER intermediate fix. An owner-operator was never observed briefing the approach by reviewing the approach plate prior to conducting the approach, though he did scroll down to the DH information at the bottom of the Jeppesen chart displayed on the MFD when he was 252 ft above DH.

Interestingly, of the six participants who briefed the approach before the start of Event 4, two actually programmed the approach at that time; the other four waited until after passing MOL when the specific approach in use was confirmed by ATC. During the post-flight debriefings, the two who programmed the approach quite early spoke of their preference to get the programming out of the way as early as possible, even if it meant having to change it later. Both of them completed the approach without difficulty.

Eleven participants programmed the approach after the end of the lost pilot scenario. Table 24 shows the relationship between the time during flight when participants prepared for or programmed the approach with difficulties they encountered while programming or conducting the approach. The more significant difficulties encountered included such things as incorrectly programming the G1000 such that the aircraft turned back toward MOL instead of toward the IAF, selecting the incorrect IAF, not activating or arming the approach, being in the wrong mode to capture the approach (i.e., HDG instead of NAV(GPS), 2 dot deflection to the right of course before being corrected, and using the AP and pitch mode to unsuccessfully chase the glideslope.

Table 24. Relationship of Timing of Approach Briefing and Programming to Encountering Difficulties in Programming or Conducting the ILS Runway 25 Approach Into KHSP.

| | All Participants (n=13) | | Owner-Operators (n=7) | | Professional Pilots (n=6) | |
|---|---|---|---|---|---|---|
| | Problem | No Problem | Problem | No Problem | Problem | No Problem |
| Timing of Briefing[1] | | | | | | |
| Very early prior to start of Event 4 | 2 | 4 | 1 | 2 | 1 | 2 |
| Between MOL and IAF[2] | 3 | 2 | 2 | 1 | 1 | 1 |
| After IAF | 1 | 0 | 0 | 0 | 1 | 0 |
| No briefing observed | 1 | 0 | 1 | 0 | 0 | 0 |
| Totals[2] | 7 | 6 | 4 | 3 | 3 | 3 |
| Timing of Programming the Approach | | | | | | |
| Very early prior to start of Event 4 | 0 | 2 | 0 | 2 | 0 | 0 |
| Between MOL and IAF[2] | 6 | 4 | 4 | 1 | 2 | 3 |
| After IAF | 1 | 0 | 0 | 0 | 1 | 0 |
| Totals[2] | 7 | 6 | 4 | 3 | 3 | 3 |

[1] When the majority of briefing activities occurred

[2] Two problems encountered were relatively minor: one participant could not locate the IAF on his IPad and did not look at other charts to find it. Another participant momentarily selected the wrong altitude for AHLER but corrected it right away.

As can be seen in Table 24, there was a fairly even split between those who did and did not encounter difficulty in programming or executing the approach. Not surprisingly, those who briefed the approach quite early in the leg tended to have fewer difficulties programming or executing the approach than participants who completed most of their briefing activities just before conducting the approach. Similarly, participants, particularly owner-operators, who programmed the approach just before or even after they had begun executing it tended to have more difficulties than those who programmed the approach earlier.

Interestingly, six of the nine participants who reported to ATC that they had obtained the weather at KHSP by checking the KHSP ASOS, landed at KHSP with an incorrect altimeter setting (29.86 instead of 29.84). Two other participants who did not report to ATC as having gotten the KHSP weather also landed with an incorrect altimeter setting (see Table 23). The incorrect altimeter setting these eight participants landed with was the Culpepper altimeter setting which was given to them when they descended through the transition altitude of 18,000 ft MSL much earlier in the flight, before Event 4 began.

***Aircraft and FAR limitations***. At no point in time did any participant exceed any aircraft or FAR limitations during Event 4. However, several flew quite fast, flying close to $V_{mo}$ (250 KIAS). In fact, a couple of participants' speeds were close to the barber pole at various times, but no one exceeded $V_{mo}$ during the event.

***Checklist and chart usage and PFD and MFD Displays***. There was no evidence that any of the participants completed any normal checklists during Event 4 and we would not have expected any. The descent checklist would likely have been performed as they started their initial descent from cruise and passed through the transition altitude of 18,000 ft MSL, which occurred before Event 4 began. Similarly, approach checklists would have been performed after Event 4 ended, at the completion of the lost pilot scenario.

However, three participants, all professional pilots, were still reviewing the abnormal checklist for ANTISKID FAIL when ATC called with the crossing restriction at the start of Event 4, and at least one pilot appeared to be thinking about this condition during Event 4 as he consulted the runway length at KHSP on the MFD to make sure he would have adequate length for landing.

Ten of the 13 pilots had a small map inset displayed on the lower left hand side of the PFD, and several of them also had traffic information (TIS) on the map. Inset map display selections can be seen in Table 25. As can be seen in this table, professional pilots were more likely than owner-operators to have either no map inset displayed or to have less information depicted on the map if it was displayed.

In the lower right corner of the PFD, seven participants had nothing displayed during Event 4. Of the remaining six participants, two displayed the timer/reference window (which displays $V_{ref}$ speeds), one displayed airport information for KHSP (later switching to a small map with waypoints depicted), and three participants displayed their flight plan during Event 4. Two of these pilots also had a larger rendition of their flight plan depicted on part of the MFD at the same time. Participants made almost no changes to their PFD inset box selections on the PFD during the event.

By far the most popular MFD display used by participants ($n$ = 9) during the event was a screen split (either left-right or top-bottom) between their flight plan and a map—seven pilots chose to show topographical information on the map, and two others chose the map view with no topographical information. The remaining four participants, all professional pilots, chose to have a large topographic map only depicted on the MFD; two of these professional pilots did not have a flight plan displayed on their PFD during the event either.

Table 25. Lower-Left PFD Inset Map Configurations.

| | All Participants (n = 10 out of 13) | Owner-Operators (n = 6 out of 7) | Professional Pilots (n = 4 out of 6) |
|---|---|---|---|
| Map only | 3 | 1 | 2 |
| Map with TIS information | 3 | 2 | 1 |
| Map with TIS and topographic information | 1 | 1 | 0 |
| Map with waypoints and TIS information | 1 | 0 | 1 |
| Map with waypoints and topographic information | 1 | 1 | 0 |
| Map with waypoints, TIS, and airspace information | 1 | 1 | 0 |

Seven participants used the Jeppesen charts on the MFD, with own-ship depiction, when conducting the ILS runway 25 approach into KHSP. Four owner-operators used electronic approach charts on an iPad. (Because the study was conducted in a simulator, no own-ship depiction could be used on the iPad approach chart as might be possible during real flights). The remaining two participants used paper approach charts. During the debriefing interviews, six mentioned that they typically have one or more backup sources for approach charts for use in the event that their primary source is not available.

***Pilot demeanor and general workload management***. A majority of the pilots displayed very professional behavior and appeared relaxed, confident, and calm during Event 4. A few displayed some minor frustration (e.g., a sigh) when encountering difficulty with programming the crossing restriction or the approach, but these displays were brief and generally mild in nature.

Three professional pilots were still referring to the ANTISKID FAIL checklist and landing data when they received the clearance for the crossing restriction at the beginning of Event 4. Two of the pilots made errors that were corrected when programming the crossing restriction—both initially placed the waypoint for the crossing restriction 15 nm after MOL instead of 15 nm before MOL. Similarly, one pilot had not finished programming the crossing restriction when the lost pilot scenario began. He also had difficulty with subsequent tasks such as correctly programming the approach at KHSP.

Over half of the participants ($n$ = 8), four owner-operators and four professional pilots, wrote down the crossing restriction clearance, and five participants wrote down information spoken by the lost pilot or ATC during the lost pilot scenario. One participant was also observed looking on his MFD for the VORs ATC was asking if the lost pilot could receive. One owner-operator was initially confused by the fundamental problem in the lost pilot scenario (i.e., ATC had lost communication and radar contact with the VFR pilot) and suggested that ATC provide vectors to the lost pilot. This same participant was also quick to ask for vectors for himself whenever he encountered a problem, we presume, as a strategy for reducing his workload. Requesting vectors was also a workload-reducing tactic employed by a professional pilot to allow more time to set up for the approach.

As described earlier, five other participants employed similar tactics during or after the lost pilot scenario to give them more time to prepare for the approach at KHSP. These tactics included pulling the power back to slow down and requesting alternate routing (vectors, a different IAF, maintaining current heading and delay turn toward the IAF). Two professional pilots offered to hold at MOL to allow for the resolution of the lost pilot scenario, although that was unnecessary; one did request a different approach fix (EXRAS) to give him more time to prepare for the approach. Despite expressing concern about not being ready for the approach, one owner-operator did very little preparation for the approach during the lost pilot scenario and employed no delaying tactics, such as reducing his speed or requesting alternate routing—he encountered quite a bit of difficulty when it came time to conduct the approach.

During leg 2, about half of the participants completed some tasks, like dialing in KHSP radio frequencies and starting to brief the probable approach, quite early. This was consistent with comments made during the debriefing interviews that their approach to workload management was to take care of as many tasks as they could as early as possible, even if it meant that some of these tasks had to be repeated later because of plan changes.

Seven participants, both owner-operators and professional pilots, seemed quite comfortable multitasking and dividing their attention between things such as talking to ATC and making power adjustments during the descent. All seven of these participants, as well as two other owner-operators, tended to interleave tasks, such as interrupting programming to make a radio call or scan the instruments, though, on occasion, an error was committed.

The remaining four participants appeared less comfortable with multitasking and approached tasks such as programming the crossing restriction and the approach in a fairly sequential and linear way. Despite this focused attention to the tasks, two of the four made errors programming the crossing restriction, and three of the four made errors programming the approach. Conversely, their focused and sequential approach to programming the crossing restriction and approach could be interpreted as an appropriate response to their programming problems, though the errors made in programming the approach were only evident after the programming had been completed and the aircraft and automation failed to behave as expected.

Table 26. Pilot Demographics by Problems Encountered With the Crossing Restriction and Instrument Approach.

| | Crossing Restriction before MOL | | | | Approach at KHSP | | | |
|---|---|---|---|---|---|---|---|---|
| | Problems (n=5) | | No Problems (n=8) | | Did not Meet (n=7) | | Met (n=6) | |
| | M | SD | M | SD | M | SD | M | SD |
| Age | 53.16 | 6.91 | 46.00 | 11.19 | 51.14 | 11.54 | 46.33 | 8.62 |
| General Flying Hours | | | | | | | | |
| Total | 4560.00 | 1192.90 | 3648.25 | 2508.82 | 3400.00 | 1831.21 | 4697.67 | 2312.95 |
| Past year | 137.00 | 44.10 | 289.00 | 169.23 | 160.71 | 92.58 | 312.00 | 175.49 |
| Past 3 months | 35.00 | 15.00 | 63.63 | 32.88 | 37.86 | 18.90 | 69.83 | 33.30 |
| Single pilot jet | 484.00 | 510.73 | 236.38 | 99.81 | 401.43 | 438.77 | 250.17 | 120.60 |
| Citation Mustang-Specific Hours | | | | | | | | |
| Past year | 127.00 | 47.38 | 170.38 | 107.97 | 139.29 | 84.82 | 170.50 | 100.06 |
| Single pilot in past year | 102.00 | 67.51 | 161.25 | 113.67 | 120.71 | 96.93 | 159.17 | 108.01 |

***Pilot background and experience***. Table 26 presents the piloting experience of participants who did and did not encounter problems with the crossing restriction prior to MOL and the approach into KHSP. A factorial MANOVA revealed no significant main effects[3] for differences in any type of flight hours assessed associated with encountering problems with the crossing restriction before MOL, problems with the approach at KHSP, or an interaction between the two, Wilk's $\lambda$ = .54, $F(6,4) = 0.57$, $p = .74$.

[3] Statistics for non-significant main effects are available upon request.

Table 27. NASA RTLX Ratings by Problems Encountered With the Crossing Restriction 15 nm Before MOL.

| | Problems (n=5) | | No Problems (n=8) | |
|---|---|---|---|---|
| | M | SD | M | SD |
| Mental Demand | 51.20 | 32.24 | 37.00 | 23.44 |
| Physical Demand | 32.20 | 26.82 | 25.50 | 19.77 |
| Temporal Demand | 40.60 | 33.59 | 38.50 | 21.66 |
| Performance[1] | 37.80 | 27.52 | 23.88 | 10.85 |
| Effort | 46.20 | 27.68 | 34.00 | 16.86 |
| Frustration | 42.40 | 30.96 | 18.63 | 16.69 |
| Average RTLX rating for event | 41.73 | 25.26 | 29.58 | 16.58 |

[1] Reverse scored so direction is consistent with all ratings of other subscales (low numerical rating = lower perception of workload demand). With reverse scored performance ratings, low ratings indicate better evaluations of one's performance.

Tables 27, 28, and 29 present differences among the same four subgroups in their subjective ratings of workload as measured by the ISA and NASA TLX measures. These ratings are presented relative to how well the pilots accomplished the crossing restriction, assisted the lost pilot, and performed the instrument approach at KHSP, respectively. Factorial MANOVAs revealed no interaction or main effects of participant problems with the crossing restriction or the instrument approach at KHSP on any of the ISA or RTLX ratings of workload.[4]

[4] Non-significant interaction and main effect statistics are available upon request.

Table 28. ISA and NASA RTLX Ratings for the Lost Pilot Scenario by Problems Encountered With the Crossing Restriction and Instrument Approach.

| | Crossing Restriction before MOL | | | | Approach at KHSP | | | |
|---|---|---|---|---|---|---|---|---|
| | Problems (n=5) | | No Problems (n=7) | | Problems[1] (n=6) | | No Problems (n=6) | |
| | M | SD | M | SD | M | SD | M | SD |
| ISA Rating | | | | | | | | |
| MOL VOR | 2.40 | 1.14 | 2.33 | 1.03 | 2.33 | 1.03 | 2.40 | 1.14 |
| NASA TLX Ratings - Assist Lost Pilot and ATC with Comms | | | | | | | | |
| Mental Demand | 57.40 | 24.61 | 54.86 | 25.61 | 57.00 | 24.56 | 54.83 | 26.04 |
| Physical Demand | 32.60 | 29.36 | 32.00 | 28.13 | 28.50 | 27.91 | 36.00 | 25.77 |
| Temporal Demand | 50.20 | 21.15 | 46.86 | 21.20 | 52.17 | 22.70 | 44.33 | 16.22 |
| Performance[2] | 25.60 | 7.30 | 14.71 | 7.66 | 22.50 | 7.82 | 16.00 | 10.87 |
| Effort | 58.00 | 24.57 | 53.29 | 21.81 | 54.67 | 26.88 | 55.83 | 15.12 |
| Frustration | 35.60 | 23.42 | 37.14 | 17.46 | 38.33 | 23.97 | 34.67 | 14.95 |
| Average RTLX rating for event | 43.23 | 15.75 | 39.81 | 16.46 | 42.19 | 17.26 | 40.28 | 13.96 |

[1] Problems experienced by two participants during the approach were relatively minor.

[2] Reverse Scored so direction is consistent with all ratings of other subscales (low numerical rating = lower perception of workload demand). With reverse scored performance ratings, low ratings indicate better evaluations of one's performance.

Table 29. ISA and NASA RTLX Ratings by Problems Encountered With the ILS or LOC RWY 25 Instrument Approach Into KHSP

| | Problems[1] (n=7) | | No Problems (n=6) | |
|---|---|---|---|---|
| | M | SD | M | SD |
| ISA Rating | 2.33 | 0.82 | 2.83 | 0.98 |
| AHLER + 15 s | | | | |
| NASA TLX Ratings - Instrument Approach at KHSP | | | | |
| Mental Demand | 52.86 | 25.65 | 53.33 | 27.04 |
| Physical Demand | 35.43 | 32.11 | 40.33 | 25.75 |
| Temporal Demand | 44.43 | 28.13 | 41.83 | 17.72 |
| Performance[2] | 30.00 | 27.83 | 20.17 | 5.72 |
| Effort | 57.43 | 24.12 | 52.00 | 27.18 |
| Frustration | 36.14 | 33.69 | 38.17 | 22.13 |
| Average RTLX rating for event | 42.71 | 26.60 | 40.97 | 18.91 |

[1] Problems experienced by two participants during the approach were relatively minor.

[2] Reverse scored so direction is consistent with all ratings of other subscales (low numerical rating = lower perception of workload demand). With reverse scored performance ratings, low ratings indicate better evaluations of one's performance.

**Voice Analyses Across the Four High Workload Events**

Voice analyses during pilot communication across the high workload events were conducted. In addition to the four high workload events, four events we expected to be of relatively lower workload (LW) were also identified.[5] Participant's fundamental frequency (vocal pitch) during the high workload (HW) events was compared to their fundamental frequency ($F_O$) during 1) the low workload (LW) events, 2) a baseline vocal sample taken while the pilot flew a pattern prior to completing the familiarization and experimental flights, and 3) a probe from ATC asking the participant to confirm his remaining route of flight during leg 2 of the experimental flight.

The baseline sample was taken early in the simulator session, when fatigue would not be a factor, during a relatively low workload period when the participant was performing a highly practiced task (flying around the pattern at an airport). The probe sample was also taken during a relatively low workload period but occurred later in the day, during the second leg of the experimental flight. The baseline and probe samples both included part of the participants' cleared route of flight to allow for comparison of the words spoken. Findings from previous literature examining $F_O$ (Huttunen, Keränen, Väyrynen, Pääkkänen, & Leino, 2011; Mendoza & Carballo, 1998; Patil & Hansen, 2007) led us to hypothesize that participant's $F_O$ during the four HW events would be significantly higher than their $F_O$ during any of the other three (LW, baseline, and probe), which were each expected to involve less workload.

[5]LW1: Pilots readback to ATC saying, "Clear of traffic, climb FL200, call NY" and Pilots call to NY and reply to report reaching

W2: Pilots reply to ATC saying, "Contact Potomac departure" and pilots call to Potomac approach and readback to ATC instructions for landing

W3: Pilot reply to ATC, "Climb back to 12000 and call NY" and pilot call to NY

W4: Pilot call to Unicom at KHSP

Table 30 provides descriptive statistics for $F_O$ used in analyses across the various events.

Two repeated measures ANOVAs were conducted to determine if any significant differences in $F_O$ existed between the four events classified as HW and the four events classified as LW. The results of the two ANOVAs revealed that no significant differences existed within the high and low workload events (HW: $F(3,27) = 2.248$, $p = .106$; LW: $F(3,33) = 1.396$, $p = .262$). Since neither finding was significant, the four HW events were combined, and the four LW events were combined for subsequent analyses.

A repeated measures ANOVA was then conducted to investigate our hypotheses that high levels of workload would yield greater fundamental frequencies than lower workload. The results of the ANOVA, with the Greenhouse-Geisser correction, did not support our hypothesis, and no significant differences in $F_O$ were found to occur between the HW events, LW events, baseline, or probe, $F(1.597,15.972) = 0.412$, $p = .625$.

Table 30. Fundamental Frequency Descriptive Statistics (Hz).

| | N | Mean | Standard Deviation | Maximum | Minimum |
|---|---|---|---|---|---|
| Baseline | 11 | 115.26 | 14.16 | 137.96 | 96.93 |
| Probe | 13 | 118.97 | 12.69 | 144.18 | 99.74 |
| HW Event 1 | 11 | 112.44 | 9.16 | 128.46 | 100.31 |
| HW Event 2 | 12 | 114.07 | 14.41 | 140.85 | 92.84 |
| HW Event 3 | 13 | 118.84 | 12.63 | 137.95 | 97.63 |
| HW Event 4 | 12 | 115.94 | 143.77 | 143.97 | 98.37 |
| Average HW | 13 | 116.28 | 12.75 | 139.19 | 97.43 |
| LW Event 1 | 12 | 115.58 | 15.54 | 140.36 | 91.86 |
| LW Event 2 | 12 | 114.10 | 14.54 | 138.19 | 90.80 |
| LW Event 3 | 13 | 120.03 | 14.69 | 142.09 | 98.68 |
| LW Event 4 | 12 | 116.83 | 14.06 | 137.9 | 92.35 |
| Average LW | 13 | 115.64 | 13.59 | 138.03 | 93.01 |

LW = low workload, HW = high workload

As with the $F_O$ analysis, a series of repeated measures ANOVAs were conducted to compare the articulation rates of participants in HW and LW events, as well as to the baseline and probe. Based on findings from previous studies (Brenner, Doherty, & Shipp, 1994; Gorovoy, Tung, & Poupart, 2010) it was hypothesized that participants' articulation rates during the four HW events would be significantly higher than rates during the LW events, baseline, and probe (i.e., participants would speak faster during higher workload events). Table 31 provides descriptive statistics for the articulation and speech rates across the various events.

Two repeated measures ANOVAs were conducted to determine if any significant differences in articulation rate among the HW events and among the LW events existed. No differences in articulation rate were found to exist for the HW events, again using the Greenhouse-Geisser correction, $F(1.613, 17.743) = 0.304$, $p = .695$. However, a significant difference in articulation rate was found to occur in the LW events, $F(3,33) = 7.370$, $p = < .01$, partial $\eta^2 = .401$. As a result of this significant finding, the data from the LW events could not be combined, and the hypothesis that higher levels of workload would yield greater articulations rates, as compared to rates during the LW events, could not be investigated.

However, since no significant differences were found to exist among the four HW events, the HW data from the four events were combined and comparisons to the baseline and probe were conducted. A repeated measures ANOVA was conducted and a statistically significant difference in articulation rates was found to exist among the three groups, $F(2,20) = 5.522$, $p < .05$, partial $\eta^2 = 0.522$. Post-hoc analysis with a Bonferroni adjustment revealed that articulation rates were significantly greater during the HW events than the probe ($p < .05$); however, no differences were found in articulation rate between the HW events and the baseline ($p = .184$) or between the baseline and the probe ($p = 1.00$).

Although the results of the analyses do not support our hypotheses that $F_O$ and articulation would increase during high workload, they may indicate that our sections of low workload were not truly low workload. Throughout the flight, there were several time periods that could have been considered low workload, such as when the pilot was en route during cruise; however, at these times the ATC and pilot made no verbal exchanges which were required for a vocal analysis to take place. During each of the LW sections used in the analysis, the pilots either had to read back an instruction, state their route, or state their future intentions. Although we believed these exchanges to be of lower workload than those occurring during the HW sections, it could be argued that the increase in cognitive load caused by the LW tasks could have influenced $F_O$ and articulation rate.

We did find a significant difference in articulation rate between the HW sections and the probe, however, which may validate a difference in pilot's workload between the tasks. Finally, it should be noted that the baseline was taken when the pilots were performing a circuit around the pattern to become familiar with the simulator. Even though the baseline was sampled after they rolled out on downwind performing a task with which they are highly familiar, but because it was a new flying environment for them, the level of workload they experienced could have been higher than we anticipated.

Results of the analysis of pilot communications with ATC (i.e., what was actually said by the participants, as opposed to the vocal qualities of spoken communication discussed above) is described in Christopher (2013).

Table 31. Articulation Rate Descriptive Statistics.

| | N | Mean | Standard Deviation | Maximum | Minimum |
|---|---|---|---|---|---|
| Baseline | 11 | 3.72 | 0.38 | 4.44 | 3.19 |
| Probe | 13 | 3.60 | 0.30 | 4.06 | 3.15 |
| HW Event 1 | 13 | 4.03 | 0.34 | 4.64 | 3.39 |
| HW Event 2 | 13 | 4.04 | 0.24 | 4.43 | 3.71 |
| HW Event 3 | 13 | 4.10 | 0.57 | 5.23 | 3.04 |
| HW Event 4 | 12 | 4.04 | 0.26 | 4.39 | 3.63 |
| Average HW | 13 | 4.05 | 0.37 | 5.23 | 3.04 |
| LW Event 1 | 13 | 4.24 | 0.52 | 4.96 | 3.53 |
| LW Event 2 | 13 | 3.91 | 0.43 | 4.44 | 3.23 |
| LW Event 3 | 13 | 4.18 | 0.51 | 4.89 | 3.19 |
| LW Event 4 | 12 | 3.72 | 0.46 | 4.49 | 2.94 |

LW = low workload, HW = high workload

## Overall Performance across the Four High Workload Events

The number of participants who were and were not successful or who did and did not experience problems in completing the major tasks within the four high workload events varied. Table 32 summarizes those numbers but only considers errors that were directly associated with a significant problem encountered while completing a task. Recall that all participants, both owner-operators and professional pilots, committed a variety of errors during all four high workload events (e.g., readback error, airspeed violation), but most were not directly related to overall task success. Also recall that it is possible that earlier problems, such as difficulty with the FD failure, may have led to later problems or caused stress whose residual effects may have made later problems more likely; however, we have no way of determining the degree to which this may have occurred.

As can be seen in Table 32, approximately two-thirds of the major tasks in the four events were accomplished by the participants with no difficulties. Overall, a greater percentage of professional pilots than owner-operators were successful, but we did not find differences in the success rates between these two groups to be statistically significant. Furthermore, the only event for which task success had a significant relationship with flight experience was Event 1, setting up the BWZ radial intercept. There were no other significant differences found in task success in the other three high workload events related to hours of flight time accrued.

The difficulties associated with the FD failure aside, most of the problems participants encountered with the successful completion of these tasks involved some sort of G1000 programming error. Consistent with that finding is the result that half or more of the participants were unsuccessful or had problems accomplishing the three major tasks that involved the greatest amount of programming: setting up for the BWZ radial intercept, programming the reroute with the crossing restriction at DQO, and setting up for the ILS approach at KHSP. The high degree of distraction caused by the unscripted FD failure likely contributed to the lack of success in setting up for the BWZ radial intercept for five participants. It is also possible that residual stress related to the FD failure contributed to some of the difficulties five of the eight participants had in programming the reroute and meeting the crossing restriction at DQO, though we have no observations or evidence to support or refute that. However,

Table 32. Success in Accomplishing Major Tasks in the Four High Workload Events.

| | All Participants (n=13) | | Owner-Operators (n=7) | | Professional Pilots (n=6) | |
|---|---|---|---|---|---|---|
| | Successful/ No Problem | Unsuccessful/ Problem | Successful/ No Problem | Unsuccessful/ Problem | Successful/ No Problem | Unsuccessful/ Problem |
| Set up BWZ radial intercept | 7 | 6 | 2 | 5 | 5 | 1 |
| Reroute with crossing restriction at DQO | 5 | 8 | 3 | 4 | 2 | 4 |
| Expedited Descent | 13 | 0 | 7 | 0 | 6 | 0 |
| Crossing restriction before MOL | 9 | 4 | 5 | 2 | 4 | 2 |
| ILS approach at KHSP | 7 | 6 | 3 | 4 | 4 | 2 |
| Totals: n | 41 | 24 | 20 | 15 | 21 | 9 |
| Totals: percent | 63 | 37 | 57 | 43 | 70 | 30 |

such "downstream" effects of stress and workload have been noted by other aviation researchers (e.g., Dismukes et al., 2007; Stokes & Kite, 1994). The difficulties approximately half of the participants had in programming and/or executing the ILS approach at KHSP is more difficult to understand, especially given that this is a commonly executed procedure that the automation design was intended to support well. As this task came at the end of two fairly demanding experimental flights and a long day in the simulator, it is possible that fatigue may have played some role but again, we have no data to confirm or negate this assertion.

Figure 20 shows the relative NASA TLX subjective ratings made by participants who were or were not successful across the five major tasks in the four events. Readers are reminded that the performance ratings had to be reversed-scored so that lower ratings are indicative of higher, or better, estimation of performance. It is not surprising to note that participants who were successful or encountered no problems in accomplishing a task tended to rate their performance much higher than those who were unsuccessful or did have problems, often by a substantial margin.

## DISCUSSION

This exploratory study examined workload management in single-pilot VLJ/ELJ operations. Our analyses for this report focused on workload strategies and performance during four high workload events that occurred during the en route portion of flight—after initial climb out and before initiation of approach and landing. As an exploratory study, we did not develop a number of detailed hypotheses to test but rather constructed experimental flight scenarios with realistic tasks in a relatively demanding operational environment. We were interested in learning about how single pilots flying an ELJ managed their workload and how they used automation for accomplishing various flight tasks. We were especially interested in problems they had, and possible reasons why, as well as in identifying strategies for task management and automation use that worked out particularly well (i.e., "best practices"). This study was also conducted to gather baseline information on single-pilot operational behavior for reference in future studies. Therefore in the Results section,

**Familiarization Flight - Comms**

| | Aircraft Location | Active Radio Freq. | Trigger | Alternate/ Notes | Pilot Task | ATC/ Flight Watch Comms | Mustang Pilot (Study Participant) Comms | Other Pilots - Live Comms | Recorded Comms (ATIS, AWOS, Background Chatter) |
|---|---|---|---|---|---|---|---|---|---|
| | AXODY, climbing to 11,000 ft. | 128.4 (Fort Worth Center) | Aircraft is at AXODY | | Respond to ATC Traffic Call | "Citation 510C You have crossing traffic at 4000, right to left, 2 o'clock and ten miles, a Citation Sovereign." | | | |
| | | | | exact comms will vary depending upon if pilot sees traffic | | | (pilot acknowledges traffic call - looks for traffic) | | |
| | | | | | | "Sovereign 36V, You have crossing traffic at **XXXX** feet climbing, crossing left to right 10 o'clock and ten miles, a Citation Mustang" | | | |
| | | | | | | | | 36V has traffic | |
| | | | | | monitor level off at 11,000 ft | | | | |
| **Cruise** | | | | | | | | | |
| | on assigned route, 11,000 ft. | | Aircraft is 15 nm before LIONS | | Respond to ATC Traffic Call | "Citation 510C You have crossing traffic at 8000, right to left 2 o'clock and five miles, an A320" | | | |
| | | | | exact comms will vary depending upon if pilot sees traffic | | | (pilot acknowledges traffic call - looks for traffic) | | |
| | | | | | | "Frontier 1449, you have crossing traffic at 11,000, left to right at 10 o'clock and 4 miles, a Citation Mustang" | | | |
| | | | | | | | | "Lookin' for the little fella, Frontier 1449" | |
| | | | | | | | | | Will Rogers Oklahoma City Airport Information BRAVO 1655 Zulu automated weather, wind is 230 at 5 gusting to 14, visibility 10 miles, 25,000 few, temperature 30, dew |

*Figure 4.* Excerpt of the Familiarization Scenario Script.

we have reported findings related to such things as G1000 PFD and MFD features used, radio set-up, and checklists in addition to the topics of primary interest here (i.e., automation use and workload management). Although they each pertain to pilot workload and task management, for the most part we will not discuss those ancillary findings here.

We remind readers that our discussion of findings related to single-pilot workload management and automation use pertains only to the tasks presented in the scenarios. Additionally, caution should be exercised when generalizing our findings to the population of VLJ/ELJ pilots as a whole because of our small sample size and potential confounds: participant self-selection, participant willingness and ability to travel to the experiment site, and a lack of representative participant gender distribution. Furthermore, our small sample size contributed to low statistical power, so our analyses were susceptible to type II errors (i.e., significant differences that truly existed were not identified by the statistics). However, findings that were found to be statistically significant *do* indicate true differences among the pilots who participated in this study.

**Participants**

When manufacturers' intent to produce VLJs came to the fore almost a decade ago, some in the industry expressed concern that owner-operators, in particular, might have some difficulties in managing workload in such advanced high performance aircraft (FSF, 2005; NBAA, 2005). Professional pilots, by the very nature of their jobs, tend to accrue more hours of flying each year and often undergo recurrent training more frequently than owner-operators. Therefore, when we planned this study we intended to study workload management strategies and automation use by owner-operators, rather than by professional pilots. However, due to scheduling issues and the rates at which owner-operators volunteered to participate, we ended up with a participant pool representing half of each pilot type.

Interestingly, we found few significant differences between the two groups with regard to flight experience in all aircraft or in the Citation Mustang alone (total hours flown, hours flown in the past year or preceding three months, single-pilot hours) or in their reported experience and skill with different types of advanced avionics. We found no significant differences in performance, errors made, or success rates in accomplishing the major tasks analyzed due to pilot type.

It is possible that the owner-operators in our study were more experienced than most and/or that owner-operators with less experience or skill did not volunteer to participate. It is also possible that the professional pilots who participated in the study fly less frequently or are less capable than those who did not participate. We have no evidence or reason to believe that this is so and can only reiterate that, as groups, the owner-operators and the professional pilots in our study performed equally well. Additionally, unlike in other studies (Kennedy, Taylor, Reade, & Yesavage, 2010; Tsang & Shaner, 1998) we found no significant difference in task success as a function of age, which ranged from 29 to 61 years ($M$ = 48.9 years).

**Workload Management**

The two legs of the experimental flight were designed to involve a fairly high degree of workload but various conditions that were unplanned and unexpected added to the workload experienced by our participants. Eight participants had to deal with an unscripted FD failure at the same time they were accomplishing the scripted tasks. Additionally, many pilots reported difficulty hearing ATC because of problems with the simulator audio system, and most pilots occasionally used a flashlight when referring to paper checklists and charts due to insufficient lighting in the simulator. Although certainly not intended, these conditions replicated the less than ideal conditions that exist from time-to-time in the real operational environment. All participants in our study persisted and responded to these problems with professionalism.

Workload management when piloting technologically advanced aircraft involves the allocation of mental resources to accomplish multiple tasks concurrently. There are three main theories in cognitive psychology with regard to how this might be done. According to the single channel theory (SCT; Broadbent, 1958), individuals complete tasks sequentially and only move on to a new task when all of the steps for the first task have been completed. In contrast, the single resource theory (SRT; Kahneman, 1973) suggests that an individual can allocate mental resources to multiple tasks concurrently. Multiple resource theory (MRT; Wickens, 2002, 2008) extends SRT by proposing that concurrent tasks can be most efficiently accomplished when they do not require the same resource, such as vision, and instead utilize two different resources, such as vision and hearing. We witnessed approaches to workload and task management in this study supportive, to some degree, of all three theories.

Most participants completed short tasks in their entirety, such as dialing in a new altitude, before moving on to other tasks (SCT). Some participants also demonstrated a similarly focused method when programming the G1000 (also SCT). Almost all performed other tasks concurrently such as dialing in a new heading while listening to the rest of an ATC clearance (MRT). Many participants also interleaved the steps associated with two or more tasks, both requiring the same resource, such as when they interrupted programming the G1000 to perform an instrument scan ("SRT",[6] both requiring vision). As would be expected, most participants chose to interleave more lengthy automation programming with other cockpit tasks. This generally increased the amount of time required to complete the programming as compared to not attending to other tasks concurrently and focusing on programming alone. However, contrary to what one might expect, those who programmed the G1000 without interruption, e.g., for the approach at KHSP or to meet a crossing restriction, made just as many programming errors as those who interleaved other tasks while programming.

Participants utilized a variety of techniques to deal with workload that had increased to such a degree as to threaten task completion. Some, but not all, participants experiencing high workload chose to slow the aircraft down to buy time. Likewise, on occasion we witnessed someone shedding or truncating a task, such as acknowledging an ATC traffic alert with only one's aircraft call sign and then not personally scanning for the traffic. These two strategies tended to be used less often than others we witnessed such as requesting vectors or alternate routing from ATC. In future studies, it would be informative to evaluate the use of strategies for excessive workload management that are

[6]SRT posits that two tasks can be performed at the same time; whereas here, pilots performed two tasks concurrently, both requiring the same resource—vision, by interleaving the steps associated with each and alternating between them.

controlled by the pilot (e.g., slowing the aircraft, shedding tasks) as compared to those involving assistance from the outside (i.e., ATC). Both are certainly necessary and appropriate in various situations. We found that those who utilized methods under their own control, such as by reducing airspeed, often accomplished the scripted tasks successfully. Please note, however, that rarely were participants in our study given vectors they requested from ATC as we did not want them to shortcut the flights and bypass scripted tasks.

Almost all participants were proactive in reducing later workload by taking care of some tasks as early in the flight as possible. This longstanding principle of completing as many tasks as possible during low workload periods to reduce the number that must be performed during periods of higher workload (FAA, 2008b; Jeppesen Sanderson, 2002) generally worked well for our participants, particularly the two who programmed the approach at KHSP very early. It would be interesting to examine, in a future study, the efficacy of this strategy for programming instrument approaches even if it means that changes are required later.

An important part of workload management involves the ways in which tasks and subtasks are prioritized relative to each other (Funk et al., 2003; Hoover, & Russ-Eft, 2005; Morris & Leung, 2006). During post-flight debriefings, most pilots reported that they subscribe to the aviate-navigate-communicate (ANC) scheme for prioritizing tasks and structuring the management of workload, even though some of them did not demonstrate this in practice during the study. ANC has long been taught and may have made sense as an approach to task prioritization in legacy cockpits with traditional round dials and primitive or no autopilots. However, we were curious about whether this scheme still makes sense in glass cockpits, with advanced autoflight systems and high AP use. The lack of eye tracking data in our study kept us from being able to test any hypotheses, but we believe that this is certainly a question that warrants further research.

ANC aside, we found that task prioritization relative to the amount of time available was essential in leading to task success. Nowhere was this more evident than in the reroute task in which participants were given minimal time to understand the reroute clearance and enter in the first new waypoint before the AP was to direct a turn. Time available was also a factor related to task success for those participants who had not adequately briefed and prepared for the instrument approach at KHSP prior to the end of the lost pilot scenario. In both cases, delaying actions or a request for vectors or alternate routing often became necessary because the participants had not or had not been able to conceptualize the tasks in terms of their temporal demands and respond accordingly.

**Automation Use**

There are three main types of automation that exist on highly automated aircraft such as the Cessna Citation Mustang: information, control, and management (Billings, 1997). Information automation pertains to all of the sources of information available and presented to the pilot on the PFD and MFD such as airspeed, traffic, engine parameters, moving maps, and alerts. Control automation pertains to actual aircraft control through stick, rudder, and yoke inputs in a fly-by-wire aircraft, which was not a factor in this study, and control of the aircraft through the autoflight system which was.[7] Also of interest in this study was pilot use of management automation, such as G1000 programming for directing aircraft flight path.

As would be expected in a jet, participants in this study used the autoflight system 90% or more of the time when flying the two legs of the experimental flight. Professional pilots tended to use it slightly less and engaged the AP at somewhat higher altitudes after takeoff than did the owner-operators, but the differences between the two groups of pilots were not great. When performing common activities using the G1000, our participants generally made inputs that were quick and sure, and they appeared to have little difficulty finding information they desired through the MFD. Exceptions to this were the difficulties some participants had in programming the reroute and the instrument approach at KHSP, both relatively common tasks. These results will be discussed later.

There were multiple ways in which our participants could use the control and management automation to accomplish the major tasks analyzed for this report, each representing different levels at which the automation or the pilot was responsible for managing the task (Billings, 1997; Parasuraman, Sheridan, & Wickens, 2000). For example, when descending to make a crossing restriction, the participants who used VPTH were using the most advanced G1000 function for accomplishing the task. After the participant programmed the VPTH descent correctly, the automation was responsible for initiating and managing the descent and ensuring the aircraft was at the proper altitude to make the crossing restriction. In contrast, participants who used VS for the descent had few steps to complete when setting up and engaging VS mode but were responsible for deciding when to initiate the descent and for choosing the descent rate. These participants also had to monitor the closure rate with the waypoint where the crossing restriction was to be met and make adjustments to airspeed and/or descent rate if it appeared they would end up high. Thus, less "advanced" automation functions tend to result in higher ongoing workload for the pilots but required less workload initially in programming or setting up the automation.

We found that when participants were confronted with high workload, they tended to opt for a lower level of automation to reduce their workload in the moment, even though that meant their overall ongoing workload might be greater. During post-flight debriefings some participants who chose less advanced automation functions (e.g., VOR navigation rather than the GPS OBS function for the BWZ radial intercept) expressed some distrust of the automation or of "not wanting to mess up what they already had in there" indicating some lack of comfort with setting up or using the G1000 management automation to its fullest extent or in the most advanced ways possible.

We suggest that a related factor integrally connected to level of automation chosen with regard to workload management is the level or layer at which the automated function is accessible to the pilot through the avionics interface. Automated functions that are operated using the mode control panel (i.e., control automation) could be thought of as being at the zero layer of accessibility—the mode control panel is presented directly in front of the pilot at all times and no buttons must be pressed or

[7] There is not uniform agreement within the industry whether the autoflight system should be considered control automation or management automation. In this report, we consider it to be a type of control automation.

menus selected for the mode control panel to be displayed for use. Thus, to select VS mode for the descent to meet a crossing restriction, such as in Event 4, the pilot has only to reach up and, using only the mode control panel, select VS mode, a rate of descent and, ideally, an altitude at which one desires to stop. In contrast, to use management automation such as VPTH for a descent to meet a crossing restriction in the G1000, one must first bring up the flight plan on the screen, if not already displayed—down one layer of accessibility. To activate the cursor to manipulate the flight plan, the FMS button must be pressed—down a second layer. Presuming the waypoint where the crossing restriction to be met is already in the flight plan, the altitude for the restriction can be set at this accessibility layer. In the case where the waypoint is not already in the flight plan, further layers of accessibility must be reached to add the waypoint or, in the case of the task in Event 4, create an along track offset.

Working through the layers of an interface has a cognitive cost. One must first remember the proper actions to take to get to the desired layers and then determine the proper inputs to be made—both require memory (declarative and procedural) as well as other higher executive cognitive functions, such as reasoning (Anderson, 2000; Fennell, Sherry, Roberts, & Feary, 2006; Norman & Shallice, 1986). Sometimes, through design, the interface helps to prompt the pilot to get to the needed layers for making the necessary inputs. Other times, the pilot must recall how to navigate the various interface layers without such prompts or guidance. Therefore, it is highly possible that when workload was high in the current study, some participants selected a particular automation strategy based not upon level of automation (how much control the pilot or the automation had for accomplishing the task), but rather on how easily accessible the automated function was and the cognitive demand involved. Therefore, it is possible that easy accessibility with less mental effort to decrease immediate workload took precedence even if it meant that workload downstream would be greater.

When confronted with a task not commonly performed, and one for which the G1000 was not designed to support with minimal inputs, such as the BWZ radial intercept, over half of the participants seemed initially unsure how to approach programming. Of the seven participants who successfully completed the task, only one used the most advanced strategy (GPS OBS function), one with which some of the participants may have been less familiar. So again, participants may have chosen a strategy involving less cognitive demand, greater familiarity, and, in the case of VOR navigation, fewer steps to minimize their workload. It appears that efficiency in management automation use, resulting in reduced workload, is more complex than simply choosing the strategy that involves the fewest number of inputs or steps. It may also involve comfort level and familiarity with the levels of automation and programming requirements, as well as temporal and cognitive demands of the overall task. These are certainly questions requiring future study.

**Successful Task Completion and Errors**

Previous flight experience was only found to have a significant association with task success in Event 1, setting up the G1000 to intercept the BWZ 208° radial. For that task, participants who were successful had accrued significantly more total flight hours, as well as more hours over the previous 12 and 3 months, in all types of aircraft, compared with those who were not successful. Thus, our overall results for all four events are not strongly supportive of the notion that greater flight experience yields better overall flight performance. It is possible that we lacked sufficient statistical power to identify any other real effects of experience on performance that might have existed, though we are unable to know for sure.

Some of the tasks analyzed for this report are relatively common, such as programming the reroute and the instrument approach at KHSP, and the number of participants who had problems accomplishing them was unexpected. It is possible that a variety of factors contributed to these difficulties including lack of familiarity with the geographical area, residual stress associated with earlier difficulties, fatigue, and/or poor management of workload relative to the temporal demands of the tasks. If so, these factors may have required more effortful, and time consuming, controlled cognitive processing rather than the faster automatic cognitive processing typically seen when experts perform highly practiced tasks (Leach, 2005; Norman & Shallice, 1986).

When acquiring and performing a complex skill such as flying a high-performance jet as a single pilot, evidence suggests that the transition from controlled processing to automatic processing is neither a one-time event nor a permanent change (Shebilske, Goettl, & Regian, 1999). After an aspect of a task has been automated, it is sometimes necessary to bring it back under controlled processing to alter its performance or to more fully integrate it with other components of the task. Even when the entire task can be performed automatically, the operator may have to revert to controlled processing when various anomalies occur. This reversion to controlled processing was likely occurring at a higher frequency among the pilots in this study because the routes and airfields were unfamiliar to most of them, the overall workload of the flights was greater than many reported being used to, and performance difficulties generally require more effortful controlled processing to sort out (Norman & Shallice, 1986).

Some of the problems participants experienced and errors they committed evidenced various cognitive failures. For example, forgetting to delete non-pertinent waypoints from a flight plan or enter in all the new waypoints in a reroute, forgetting to check in with a new controller, and forgetting to select a lateral or vertical mode or complete a step in using the autoflight system are all examples of prospective memory failure—forgetting to perform an intended action at some later point (Boer, 1997; Dismukes, 2010). Many, if not all of the prospective memory failures, may have occurred because of distraction or interruptions (Dodhia & Dismukes, 2009). Distraction, sometimes self-induced, was also likely a factor in participants making some programming errors, particularly when experiencing the FD failure, and in not catching some errors for several seconds after the aircraft behaved differently than intended.

Although Wiener (1989) found that in highly automated aircraft, pilot capacity and productivity increases along with a decreasing manual workload, more precise handling of the systems is required and there is more room for input errors. Wioland & Doireau (1995) found that pilots were able to detect 70% of their own input errors; however the detection rate fell to 40% when pilots were tasked with detecting automation errors and errors committed by their co-pilots.

In addition to input or programming errors, in the current study we also observed some related problems with cognitive

processing (e.g., not understanding who could hear whom in the lost pilot scenario). Other errors appeared associated with some confusion about how the automation worked (e.g., reversion to roll mode when the AP is on but a lateral mode has not been chosen). Obviously all the errors just described that are of a cognitive nature provide further support for the idea that highly automated aircraft place a heavy cognitive load on the pilot (e.g., Burian & Dismukes, 2007; Sarter, Woods, & Billings, 1997).

However, the way in which the automation is designed can increase or decrease this load. For example, the reroute clearance in Event 2 was "Citation XXXX is now cleared to Martin State Airport via J75, Modena, direct Dupont, Victor 214 to KERNO, direct JUGMO, direct Martin State." After entering Dupont (DQO), more than one participant was clearly attempting to add the Victor 214 airway to their flight plan. However, in the Mustang G1000, an airway can be added to a flight plan only after a waypoint *following* the airway entry point has been chosen—in this case, KERNO (Garmin Ltd., 2006). In other words, the option for adding Victor 214 to the flight plan was only presented to participants after they selected KERNO; it was not available after their selection and addition of DQO. Flight plans are chronological by their nature and it is not surprising that some participants may not have remembered that an airway is inserted before a selected waypoint (i.e., going "backwards" in the flight plan) rather than after one.

Earlier, we suggested that distraction may have been a factor when some participants did not catching programming errors until the aircraft behaved in unintended ways. It is also possible that, rather than distraction, a certain amount of automation-induced "complacency" was to blame (Funk et al., 1999; Parasuraman, Molloy, & Singh, 1993). Highly automated aircraft have a high degree of reliability and over time, experienced pilots flying them may become over-reliant on the aircraft and automation to perform as expected. Many in the industry have emphasized the need for pilots to fight that urge and actively monitor automation—never just "set it and forget it" (Sarter, Woods, & Billings, 1997). It is somewhat ironic though, that automation is a boon to workload reduction, particularly in single-pilot operations, and yet, the pilot's reduced workload is increased by the need to monitor the very thing that reduced it in the first place. Despite this, we certainly found evidence that active monitoring was essential for catching programming errors. Our findings support the need, particularly in single-pilot operations, for achieving a balance between monitoring the automation and deferring to the automation to manage things so the pilot may attend to other tasks. Future research could help identify an optimal balance between these activities, as well as determine if there are some aspects of automated functioning that might require less or more monitoring overall or during certain tasks.

Some of the errors committed by participants were unexpected. For example, we were surprised by the high number of airspeed violations in Event 1. Distraction due to the unscripted FD failure may account for some, but even among those who did not experience the failure, airspeed violations were prevalent, particularly exceeding 200 KIAS below the Class B veil and in Class D airspace. Only one participant had airspace boundaries depicted on his navigation map display, and he could be heard making comments about airspace and speed limits as he flew. It is possible that the others were not as attentive to airspace as they might normally be because this was a simulation study. They may have assumed that such restrictions were not important in a study and/or have expected to be given airspeed restrictions from ATC if they were.

We were also surprised by the high number of participants who neglected to contact ATC to inform them that they had initiated their descent from 16,000 ft MSL in Event 4 ($n$ = 10) and that none of the participants who failed to meet the crossing restrictions in Events 2 or 4 contacted ATC to inform them ($n$ = 4 and $n$ = 1, respectively). These errors could represent prospective memory failures or, again, be associated with the somewhat artificial nature of a study where the participant is really the only pilot in the sky, and traffic conflicts are not truly a concern. Nonetheless, participants were instructed to fly as they normally do so it was troubling that these important radio calls were not made.

More than half of the participants ($n$ = 8) also landed at KHSP with an incorrect altimeter setting. We suspect that something other than study complacency might be related to this error. The highest cruise altitude that participants flew during leg 2 was FL200, but they were cleared to the lower cruise altitude of 16,000 ft MSL, due to traffic, when they were still 120 nm away from KHSP. When they transitioned through FL180 they were given the local altimeter setting for that area (Culpepper, VA: 29.86 mmHg). Although most participants were informed of the KHSP 29.84 altimeter setting through the KHSP ASOS, many did not note the difference and reset it. Of course, distraction could be a factor as workload was high. We also do not know if participants routinely skip adjusting the altimeter for such a small change. Another possibility is that expectations ingrained from experience, where the descent through FL180 occurs much closer to the destination airport and the altimeter setting given by ATC at that time is the setting for that airport, contributed to participants not attending to the change—a type of expectation bias. Furthermore, the descent checklist, which prompts participants to check the altimeter setting, was likely completed when they descended from FL200. This item is not repeated on either the approach or before landing checklists for the Citation Mustang. In this scenario where atmospheric changes were fairly small and gradual and visibility at the airport was relatively good, such an error made little difference. However, we believe that it is generally good practice for pilots to regularly check the local altimeter setting just prior to initiating an instrument approach for those times when conditions are not so stable or benign (e.g., NTSB, 1996).

Finally, we noted that poor flying skills were demonstrated when some participants flew manually, particularly associated with the FD failure. Our participants were not unusual in that. It has been demonstrated that after the introduction of highly automated flight systems, transport category aircraft crews were also observed with reduced proficiency in manual flying (Helmreich, Hines & Wilhelm, 1996). The concern about reduced manual flying proficiency has been echoed by many in the industry (Abbott, 2012; Masson, 2011; Turner, 2009).

During debriefing interviews and conversations during breaks, several participants discussed the importance of the autoflight system for managing their workload as single pilots. A few also expressed concerns that their manual flying skills were not as sharp as they once were. When participants were asked what they could do about that, they suggested flying the simulator manually more during recurrent training. In his research, Wiener

(1988) found that airline transport pilots flying highly automated aircraft routinely fly portions of their flights manually because of a fear of losing their basic flight skills. The Commercial Aviation Safety Team (2008) recommended that pilots of all aircraft avoid over-reliance on automation because of its potential detriment to manual flying skills. They also recommended that pilots manually fly their aircraft to maintain proficiency when flight conditions permit.

**Study Limitations and Recommended Future Studies**

There are limitations in all research and this study is no exception. The pilots in our study volunteered to participate (i.e., they were self-selected), so they may not be representative of VLJ/ELJ owner-operators and professional pilots at large. And, because this was an exploratory study, the number of pilots participating was fairly small. Therefore, statistical power was limited, which precludes our ability to generalize our findings beyond the pilots who participated.

As described earlier, there is some artificiality in flying a simulator as part of a study, so some of the ways in which our participants flew may not perfectly match the ways they fly in real life. Finally, although we allowed participants as much time to prepare for the experimental flights as they wanted, many were not familiar with the busy East Coast corridor where the flights took place. Had they undertaken those flights in real life, they might have taken considerably longer to prepare for them, perhaps even spread out over several days, and might have taken along a second pilot to help manage some of the workload. A few pilots said as much during the debriefing interviews.

Based on our findings and observations, we have a number of questions and suggestions for future research. Some have already been mentioned earlier, but all are summarized here.

- When workload is very high, does task success rate vary as a function of the type of workload management strategy employed (pilot controlled vs. asking for outside assistance from ATC)? Are some workload management strategies more or less successful for different kinds of tasks, for different phases of flight, or for single pilots vs. crews? Do the strategies differ for pilots flying jets as compared to piston aircraft?
- What is the efficacy of loading an expected instrument approach into the automation very early during a flight (i.e., while still en route)? Does any advantage found still remain if the expected approach is incorrect and the automation must be reprogrammed? Do the cost-benefit tradeoffs suggest that this is a good workload management strategy and if so, under what conditions is that true?
- Does the ANC workload prioritization scheme for single pilots make sense in glass cockpits with advanced autoflight systems and high AP use?
- Will the findings in this study that single pilots tend to revert to lower levels or more easily accessible control automation to reduce workload in the short term, even though it might entail higher levels of ongoing workload management, be found in other studies with other participants? If so, which appears to be the more significant driver in automation selection: level of control or layer of accessibility/cognitive demand?
- How does pilots' baseline knowledge of control and management automation use and their mental models about automation functionality relate to different levels or types of automation actually employed to accomplish flying tasks and the rates at which they are successful in accomplishing those tasks in single-pilot operations?
- Assuming that greater automation efficiency leads to better workload management, further explore what comprises automation efficacy and does this change for different tasks? Consider the following aspects, among others:
  - » level or type of automation
  - » level of familiarity/degree of comfort with both the task and the automation employed
  - » layer of accessibility through the avionics interface
  - » number of steps required for programming/setting up the automation
  - » cognitive demands for completing the programming/set-up tasks (e.g., recognition vs. recall steps; Fennell et al., 2006)
  - » cognitive and temporal demands of the task
- Determine, if possible, the optimal balance between time spent monitoring automation and time spent focusing on other tasks, and identify if this optimal balance changes as a function of task or phase of flight
- Examine the efficacy of using instrument charts on paper vs. MFD vs. iPad/PDD or some combination of two or all three of them for navigating an IFR flight by a single pilot
- Are pilot automation use and errors committed associated with frequency of use or the use of different avionics systems in other aircraft?

**Recommendations for Workload Management and Automation Use**

We were quite privileged to witness some very fine flying by our participants in this study. Techniques observed, which we have characterized as "best practices," as well as some other things for pilots to consider, are summarized in Appendix F. Some of those best practices are also captured below in our list of recommended strategies for automation use and countermeasures to task overload and workload breakdowns. By their very nature, findings from observational studies, such as this one, do not lend themselves to generating of a lot of definitive recommendations. In the list of recommendations below, some are tentative and should be verified through future research.

- To the extent that it is feasible, pilots should consider completing short, easily performed tasks associated with ATC clearances quickly, such as dialing in a new heading while listening to the rest of the ATC clearance.
- Pilots should be prepared to copy (in writing) or audio-record an ATC clearance involving a reroute or hold and not try to rely upon their memory.
- When considering a task involving automation programming, participants should consider any time constraints related to intended automation function and time available to guide decisions about programming strategy and level or type of automation to select.
- Pilots should complete as many tasks as possible early during periods of low workload. Research is needed to evaluate the cost-benefit trade-offs of pilots programming an expected, but not confirmed, instrument approach while still at cruise.
- Pilots should avail themselves of the full range of workload management strategies such as reducing airspeed (with

notification to ATC as required), being intentional when shedding or truncating tasks, altering type of control or management automation selected, and asking for ATC assistance (vectors, a hold, etc.).

- In times of high workload when faced with needing to select a type of automation, pilots might consider the option of selecting a lower level of automation (i.e., control automation) initially to begin the task or maneuver and, if appropriate, program a higher level of automation (i.e., management automation) to complete the maneuver as soon as possible to reduce their ongoing workload. Further research is needed first to evaluate the efficacy and safety of this strategy.
- During periods of automation mode changes (e.g., level off at top of climb) pilots should briefly refrain from other tasks and monitor the automation and aircraft behavior to make sure the aircraft performs the action as intended.
- When leveling off from a climb or descent, we suggest that pilots establish a practice of putting their hands on the thrust levers to make necessary speed adjustments as they monitor the automation and aircraft behavior.
- If the autopilot is not in use, the flight director should either be programmed or disengaged to eliminate distracting flight control prompts that do not match those actually being made.
- We suggest that pilots dial in the frequency for the instrument approach in use at their departure airport, if applicable, prior to departure, and have the charts easily accessible in case they need to immediately return to the airport after takeoff.
- When deferring a task until a later time, we suggest that pilots take a moment and form an explicit intention about completing the task and when. For example, say to yourself, "Report to ATC when I level out at cruise." External memory aids or cues, such as placing an incomplete checklist between the throttle levers or on your lap, can also assist with recalling the need to perform deferred actions (Dismukes, 2010).

## CONCLUSION

Technology is intended to make our lives easier and more productive. However, there are always unintended consequences involved with the introduction and use of technology. When it is incorporated into the cockpit of an aircraft, advanced cockpit displays and automated flight systems can relieve the pilot of many of the immediate tasks associated with navigating and flying the aircraft. At the same time, these systems also introduce a need to learn and memorize a bewildering amount of procedures and information for interacting with the automation and the aircraft. Well-designed automation is required to support an effective human-automation partnership and reduce the cognitive load associated with automation use. The current study has demonstrated that the presence of advanced technology in the cockpit does not necessarily eliminate high workload events during a flight. These events can tax a pilot's cognitive resources to the point that errors in navigation and flight control occur. We hope that the recommendations and research generated from this study will lead to safety and efficiency enhancements for single-pilot operation of technologically advanced aircraft.

## REFERENCES


Abbott, K. (2012). FAA automation workshop. Presented at the August 2012 meeting of the CNS Task Force, Boston, MA.

Air Safety Institute. (2012). *The Accident Record of Technologically Advanced Aircraft*. Frederick, MD: Aircraft Owners and Pilots Association.

Aircraft Owners and Pilots Association [AOPA] (2007). Technologically advanced aircraft: Safety and training. Frederick, MD: AOPA Air Safety Foundation. Frederick, MD.

Aircraft Owners and Pilots Association [AOPA] (2012, August 6). Retrieved from http://download.aopa.org/ustprocs/current/NE-3/hsp_ils_or_loc_rwy_25.pdf

Anderson, J.R. (2000). *Cognitive psychology and its implications,* 5th ed. New York: Worth.

Billings, C.E. (1997). *Aviation automation: The search for a human-centered approach.* Mahwah, NJ: Lawrence Erlbaum Associates.

Boer, L.C. (1997). Remembering to do a task: An element of cockpit management. In H.M. Soekkha (Ed.), Aviation safety: Human factors, system engineering, flight operations, economics, strategies, management (pp 455-464). Utrecht, the Netherlands: VSP.

Boersma, Paul & Weenink, David (2012). Praat: doing phonetics by computer (Version 5.3.22) [computer software]. Available from http://www.praat.org/

Brenner, M., Doherty, E.T., & Shipp, T. (1994). Speech measures indicating workload demand. *Aviation, Space, and Environmental Medicine, 65*(1), 21-26.

Broadbent, D. (1958). *Perception and communications.* New York: Permagon.

Burian, B.K. (2007). Very light jets in the national airspace system. *Proceedings of the 14th International Symposium on Aviation Psychology*. Dayton, OH.

Burian, B.K., Christopher, B., Fry, D.G., Pruchnicki, S., & Silverman, E. (2013). Jet single-pilot simulation study scenario overviews, task analyses, and concurrent task timelines. NASA Technical Memorandum.

Burian, B.K., & Dismukes, R.K. (2007). Alone at 41,000 feet: Single-pilot operations in technically advanced aircraft. *Aero Safety World,* (11), 30-34.

Burian, B.K., & Dismukes, R.K. (2009). Single-pilot VLJ operations. *The Aerospace Professional,* 2, 17-21.

Burian, B.K., Pruchnicki, S., & Fry, D.G. (2013). Entry-level jet single-pilot human-in-the-loop simulation research: Study scripts and radio background chatter dialogue. NASA Technical Memorandum.

Burin, J. (2011). Keys to a safe arrival. *Aero Safety World,* (10), 14-17.

Byers, J.C., Bittner, A.C., and Hill, S.G. (1989). Traditional and raw task load index (TLX) correlations: are paired comparisons necessary? In A. Mital (Ed.), *Advances in Industrial Ergonomics and Safety* (pp. 481-485). London: Taylor & Francis.

Casner, S.M. (2003). Learning about cockpit automation: From piston trainer to jet transport. NASA Technical Memorandum, NASA/TM-2003-212260.

Castle, H. and Leggatt, H. (2002). *Instantaneous self assessment (ISA) validity & reliability*. JS 14865 (1). Bristol, United Kingdom: BAE Systems.

Cessna Aircraft Company. (ND). Maneuvers and Procedures. *Citation Mustang Operating Manual*. Wichita, KS: Cessna Aircraft Company

Chou, C., Madhavan, D., & Funk, K. (1996). Studies of cockpit task management errors. *International Journal of Aviation Psychology, 6*(4), 307-320.

Christopher, B. (2013). An analysis of speech factors as indictors of cognitive workload. Manuscript in preparation.

Clark, R.E., Feldon, D., vanMerrienboer, J., Yates, K, & Early, S. (2008). Cognitive task analysis. In Spector, J.M., Merrill, M.D., van Merriënboer, J.J.G., & Driscoll, M.P. (Eds.) *Handbook of research on educational communications and technology* (3rd ed.). Mahwah, NJ: Lawrence Erlbaum Associates.

Commercial Aviation Safety Team [CAST]. (2008). Mode awareness and energy state management aspects of flight deck automation. *Safety Enhancement 30* (5th rev.). Washington DC: CAST.

de Jong, N.H. & Wempe, T. (2009). Praat script to detect syllable nuclei and measure speech rate automatically. *Behavior Research Methods*, *41*(2), 385 – 390.

Deutsch, S., & Pew, R.W. (2005). *Single Pilot Commercial Aircraft Operation* (BBN Report No. 8436). Cambridge, MA: BBN Technologies.

Dismukes, R.K. (2010). Remembrance of things future: Prospective memory in laboratory, workplace, and everyday settings. In D H. Harris (Ed), *Reviews of Human Factors and Ergonomics, 6*(1), 79-122. Santa Monica, CA: Human Factors and Ergonomics Society.

Dismukes, R.K., & Berman, B. (2010). *Checklists and monitoring in the cockpit: Why crucial defenses sometimes fail.* NASA Technical Memorandum, NASA/TM—2010-216396.

Dismukes, K., Berman, B.A., & Loukopoulos, L.D. (2007). *The limits of expertise : rethinking pilot error and the causes of airline accidents*. Aldershot, Hampshire, England: Ashgate.

Dodhia, R.M., & Dismukes, R.K. (2009). Interruptions create prospective memory tasks. *Applied Cognitive Psychology, 23*(1), 73-89.

Farmer, E. and Brownson, A. (2003). *Review of workload measurement, analysis and interpretation methods* (CARE-Integra-TRS-130-02-WP2). European Organisation for The Safety of Air Navigation.

Federal Aviation Administration [FAA] (2008a). *Airline transport pilot and aircraft type rating practical test standards for airplane*. FAA-S-8081-5F. Washington, DC: U.S.: GPO.

Federal Aviation Administration [FAA] (2008b). *Instrument flying handbook.* FAA-H-8083-15A. Washington, DC: U.S. Government Printing Office.

Federal Aviation Administration [FAA] (2010). *Instrument rating practical test standards for airplane, helicopter, and powered lift*. FAA-S-8081-4E w/ changes 1 and 2. Washington, DC: U.S. Government Printing Office.

Federal Aviation Administration [FAA] (2012). *NextGen Implementation Plan*. Washington, DC: U.S. Government Printing Office.

Fennell, K., Sherry, L., Roberts, R.J., & Feary, M. (2006). Difficult access: The impact of recall steps on flight management system errors. *International Journal of Aviation Psychology, 16*(2), 175-196.

Flight Safety Foundation (FSF). (2005). Here come the very light jets. *Flight Safety Digest, 24*(7), 1-34.

Funk, K.H., Colvin, K., Bishara., S., Nicolalde, J., Shakeri, S., Chen, J.Y., & Braune, R. (2003). *Training pilots to prioritize tasks: Theoretical foundations and preliminary experiments.* Final Report, NASA Grant NAG 2-1287. Corvallis, OR: Oregon State University.

Funk, K., Lyall, B., Wilson, J., Vint, R., Niemczyk, M., Suroteguh, C., & Owen, G. (1999). Flight deck automation issues. *International Journal of Aviation Psychology, 9*(2), 109-123.

Garmin Ltd. (2006). *Garmin G1000 pilot's guide for the Cessna citation mustang*. Olathe, KS: Garmin International, Inc.

General Aviation Manufacturers Association [GAMA] (2000). *Recommended practices and guidelines for part 23 cockpit/flight deck design.* GAMA Publication No. 10. Washington, DC: author.

General Aviation Manufacturers Association [GAMA] (2005). *Recommended practices and guidelines for an integrated cockpit/flight deck in a 14 CFR part 23 certificated airplane.* GAMA Publication No. 12. Washington, DC: author.

Gopher, D., Armony, L., & Greenshpan, Y. (2000). Switching tasks and attention policies. *Journal of Experimental Psychology: General, 129*(3), 308-339.

Gorovoy, K., Tung, J., & Poupart, P. (2010). Automatic speech feature extraction for cognitive load classification. *Conference of the Canadian Medical and Biological Engineering Society (CMBEC),* Vancouver, BC.

Griffin, G.R., & Williams, C.E. (1987). The effects of different levels of task complexity on three vocal measures. *Aviation, Space, and Environmental Medicine, 58*(12), 1165-1170.

Hart, S.G. (2006). NASA-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, 904-908. Santa Monica: HFES.

Hart, S.G. & Staveland, L.E. (1988) Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock and N. Meshkati (Eds.), *Human Mental Workload* (pp. 139-183). Amsterdam: North Holland Press.

Helmreich, R.L., Hines, W.E., & Wilhelm, J.A. (1996). *Issues in crew resource management and automation use: Data from line audits* (Technical Report No. 96-2). Austin, TX: University of Texas Aerospace Crew Research Project.

Hinton, D.A. & Shaughnessy, J.D. (1984). *The pilot interface with cockpit automation and advanced avionics systems.* NASA Technical Memorandum, NASA/TM-1984-2241.

Hoh, R., Bergeron, H P., Hinton, D.A. (1983). Practical guidance for the design of controls and displays for single pilot IFR. *Proceedings from the Second Aerospace Behavioral Engineering Technology Conference.* Warrendale, PA.

Hoover, A.L., & Russ-Eft, D.F. (2005). Effect of concurrent task management training on single pilot task prioritization performance. *International Journal of Applied Aviation Studies, 5(2)*, 233-251.

Howell, W.C., & Cooke, N.J. (1989). Training the human information processor: A look at cognitive models. In I. Goldstein (Ed.), *Training and Development in Work Organizations: Frontier Series of Industrial and Organizational Psychology, Volume 3,* (pp. 121-182). New York: Jossey Bass.

Huttunen, K., Keränen, H., Väyrynen, E., Pääkkönen, R., & Leino, T. (2011). Effect of cognitive load on speech prosody in aviation: Evidence from military simulator flights. *Applied Ergonomics, 42*(2), 348-357.

Jeppesen Sanderson (2002). *Instrument commercial manual*. Englewood, CO: Author.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice Hall.

Kennedy, Q., Taylor, J.L., Reade, G., & Yesavage, J.A. (2010). Age and expertise effects in aviation decision making and flight control in a flight simulator. *Aviation, Space, and Environmental Medicine, 81*(5), 489-497.

Layton, C., Smith, P.J. & McCoy, C.E. (1994). Design of a cooperative problem-solving system for en-route flight planning an empirical evaluation. *Human Factors*, *36*(1), 94-119.

Leach, J. (2005). Cognitive paralysis in an emergency: The role of the supervisory attentional system. *Aviation, Space, and Environmental medicine, 76*(2), 134-135.

Loukopoulos, L.D., Dismukes, R.K., & Barshi, I. (2003). Concurrent task demands in the cockpit: Challenges and vulnerabilities in routine flight operations. *Proceedings of the 12th International Symposium on Aviation, Psychology.* Dayton, OH: Wright State University.

Masson, M.A. (2011). EASA Automation Policy. *Staying in control – Loss of control prevention and recovery, EASA Conference,* Cologne, Germany.

Mendoza, E. & Carballo, G. (1998). Acoustic analysis of induced vocal stress by means of cognitive workload tasks. *Journal of Voice, 12*(3), 263-273.

Miller, S. (2001). *Literature review: Workload measures* (Document ID: N01-006). Iowa City, IA: National Advanced Driving Simulator.

Morris, C.H., & Leung, Y.K. (2006). Pilot mental workload: How well do pilots really perform? *Ergonomics, 49*(15), 1581-1596.

National Business Aviation Association [NBAA] (2005). Training guidelines for very light jets and technically advanced aircraft. Retrieved from http://web.nbaa.org/ops/safety/vlj/

National Transportation Safety Board [NTSB] (1992). *Beechcraft A-36 Bonanza accident report, Chapel Hill, NC, August 11, 1989.* Aircraft Accident Report NTSB/ATL89FA196. Washington, DC: author.

National Transportation Safety Board [NTSB] (1996). *Collision with trees on final approach, American Airlines flight 1572, McDonnell Douglass MD-83, N566AA, East Granby, Connecticut, November 12, 1995* (Report No. NTSB/AAR-96/05, PB96-910405). Washington, DC: author.

National Transportation Safety Board [NTSB] (2010). Introduction of glass cockpit avionics into light aircraft. Safety study NTSB/SS-10/01. Washington, DC: Author.

Norman, D.A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In R.J. Davidson, G.E. Schwartz, & D. Shapiro (Eds.), *Consciousness and self-regulation, (*Vol. 4, pp 1-18), New York: Plenum Press. (Originally published in 1980).

Palmer, M.T., Rogers, W.H., Press, H.N., Latorella, K.A., & Abbot, T.S. (1994*). A crew-centered flight deck design philosophy for high-speed civil transport (HSCT) aircraft.* NASA Technical Memorandum, NASA/TM-1994-109171.

Parasuraman, R., Molloy, R., & Singh, I.L. (1993). Performance consequences of automation-induced "complacency." *International Journal of Aviation Psychology 3*(1), 1 – 23.

Parasuraman, R., Sheridan, T.B., & Wickens, C.D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on systems, man and cybernetics, Part A: Systems and humans, 30*(3), 286-297.

Patil, S.A., & Hansen, J.H.L. (2007). Speech under stress: Analysis, modeling and recognition. In C. Müller (Ed.), *Speaker classification I: Fundamentals, features, and methods* (pp.108-137). Berlin, Heidelberg: Springer-Verlag.

Prinzel, L.J. (2002). *The relationship of self-efficacy and complacency in pilot-automation interaction.* NASA Technical Memorandum, NASA/TM-2006-211925.

Roscoe, A.H. (1992, April). Workload in the glass cockpit. *Flight Safety Digest,* 1-20.

Ruiz, R., Legros, C., & Guell, A. (1990). Voice analysis to predict the psychological or physical state of a speaker. *Aviation, Space, and Environmental Medicine, 61*(3)*,* 266-271.

Sarter, N.B., & Woods, D.D. (1992). Pilot interaction with cockpit automation: Operational experience with the flight management system. *International Journal of Aviation Psychology, 2*(4), 303-321.

Sarter, N.B., & Woods, D.D. (1995). "From tool to agent": The evolution of (cockpit) automation and its impact on human-machine coordination. *Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting*, 79-83.

Sarter, N.B., Woods, D.D., & Billings, C.E. (1997). Automation surprises. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics* (2nd ed.). New York: Wiley.

Schutte, P.C., Goodrich, K.H., Cox, D.E., Jackson, B., Palmer, M.T., Pope, A.T., Schlecht, R.W., Tedjojuwono, K.K., Trujillo, A.C. , Williams, R.A., Kinney, J.B., and Barry, J.S. Jr. (2007). *The naturalistic flight deck system: An integrated system concept for improved single-pilot operations*. NASA Technical Memorandum. NASA/TM-2007-215090.

Shebilske, W., Goettl, B., & Regian, J.W. (1999). Executive control and automatic processes as complex skills develop in laboratory and applied settings. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application* (pp. 401-432). Cambridge, MA: The MIT Press.

Stokes, A., & Kite, K. (1994). *Flight stress: Stress, fatigue, and performance in aviation.* Aldershot, England: Ashgate.

Turner, T.P. (2009). You are the backup to safety enhancing aircraft avionics. *Aviation Safety*. Retrieved from http://www.aviationsafetymagazine.com/issues/28_8/features,8955-1.html

Tsang, P.S., & Shaner, T.L. (1998). Age, attention, expertise, and time-sharing performance. *Psychology of Aging, 13*(2), 323-347.

Wickens, C.D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomic Science, 3* (2), 1-19.

Wickens, C.D. (2008). Multiple resources and mental workload. *Human Factors, 50* (3), 449-455.

Wickens, C.D. & Hollands, J. G. (2000). *Engineering psychology and human*

*Performance* (3rd ed.). Upper Saddle River, New Jersey: Prentice Hall.

Wiener, E.L. (1981). Complacency: Is the term useful for air safety? *Proceedings of the 26th Corporate Aviation Safety Seminar (pp.116-125).* Denver: Flight Safety Foundation, Inc.

Wiener, E.L. (1988). Cockpit automation. In E. L. Wiener & D. C. Nagel (Eds.), *Human factors in aviation* (pp.433-461). San Diego, CA: Academic Press.

Wiener, E.L. (1989). *The human factors of advanced technology ("glass cockpit") transport aircraft.* NASA Contractor Report. NASA/CR-1989-177528.

Williams, K., Christopher, B., Drechsler, G., Pruchnicki, S., Rogers, J., Silverman, E., Gildea, K., Cotton, S., Mead, A., Hackworth, C., & Burian, B.K. (2013). *Aviation human-in-the-loop simulation studies: Data management and transformation approaches in preparation for analysis.* NASA Technical Memorandum.

Wioland, L. & Doireau, P. (1995). Detection of human error by an outside observer: A case study in aviation. *5th European conference on cognitive science approaches to process control*, Espoo, Finland, 54-62.

Zitt, D. (2006). Flying with glass cockpits in general aviation. Proceedings from AOPA Expo 2006. Palm Springs, CA: Aircraft Owners and Pilots Association.